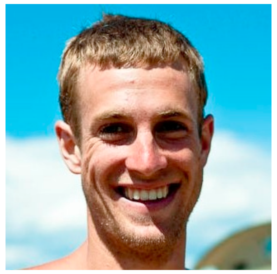
Refuting Heap Reachability

Bor-Yuh Evan Chang
University of Colorado Boulder



Sam Blackshear
CU Boulder

Manu Sridharan
Samsung

January 20, 2014
VMCAI 2014

PLV

At my first VMCAI in 2005 (Paris)

as a young PhD student

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as a young PhD student

“Spirit of VMCAI” introduced in my “formative academic years”

A bug that manifests spectacularly ...

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Wow! Android memory leaks underly rotation-based crashes.

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How?!?

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`Activity` objects encapsulate the UI

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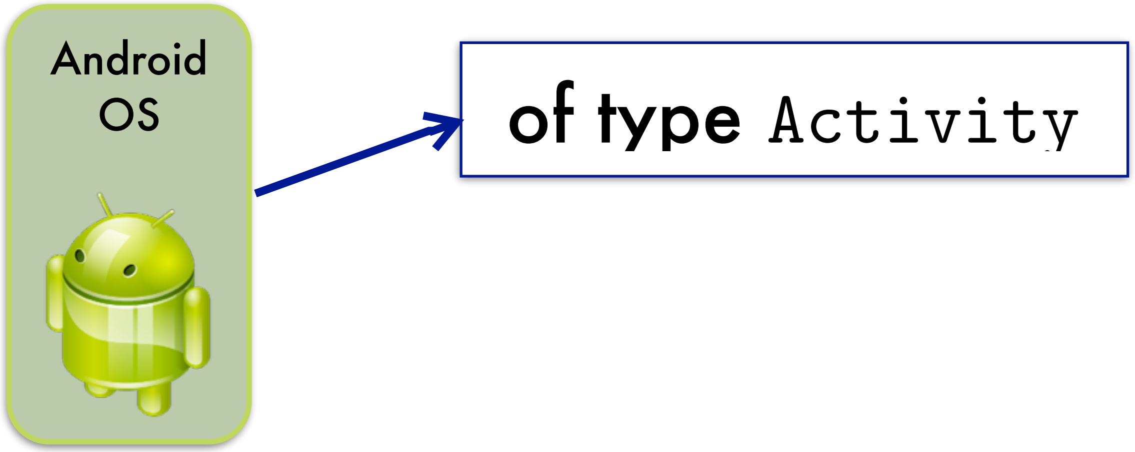

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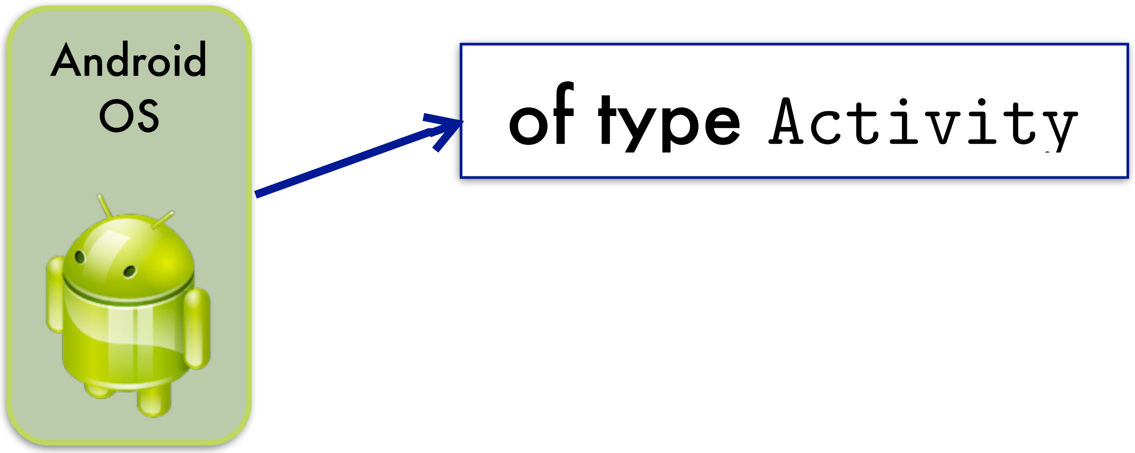

Android OS

of type `Activity`

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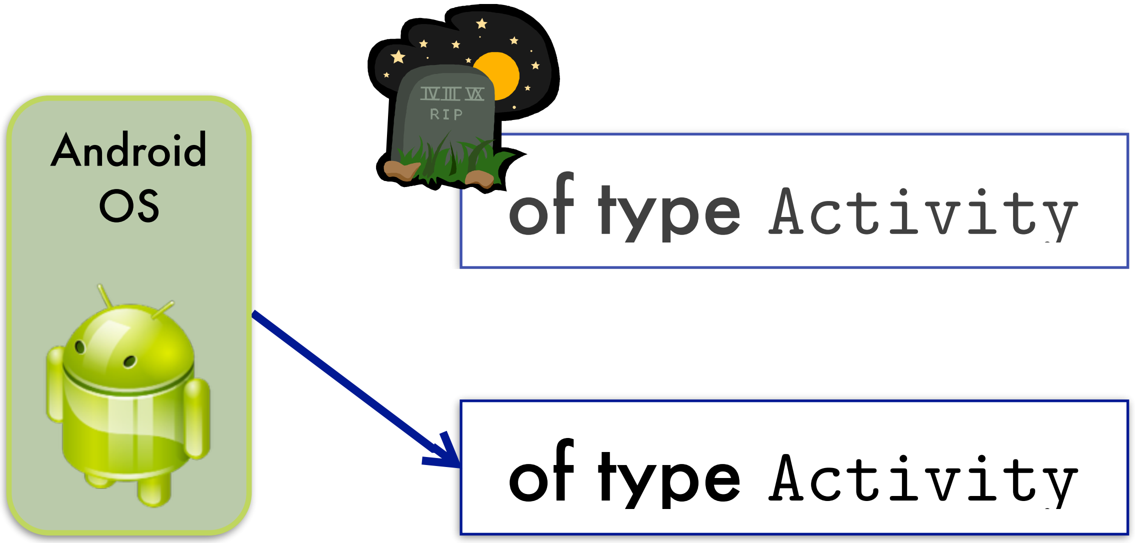

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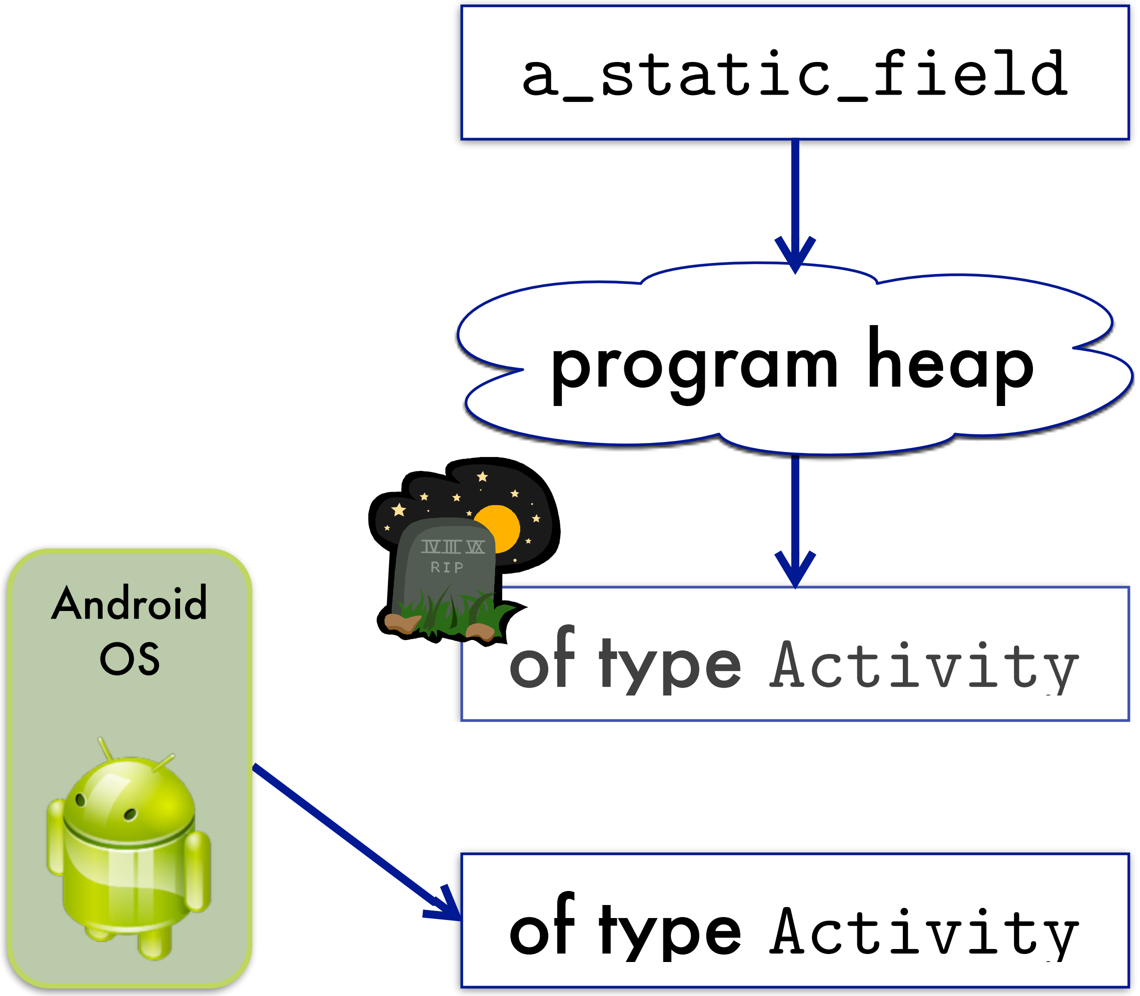

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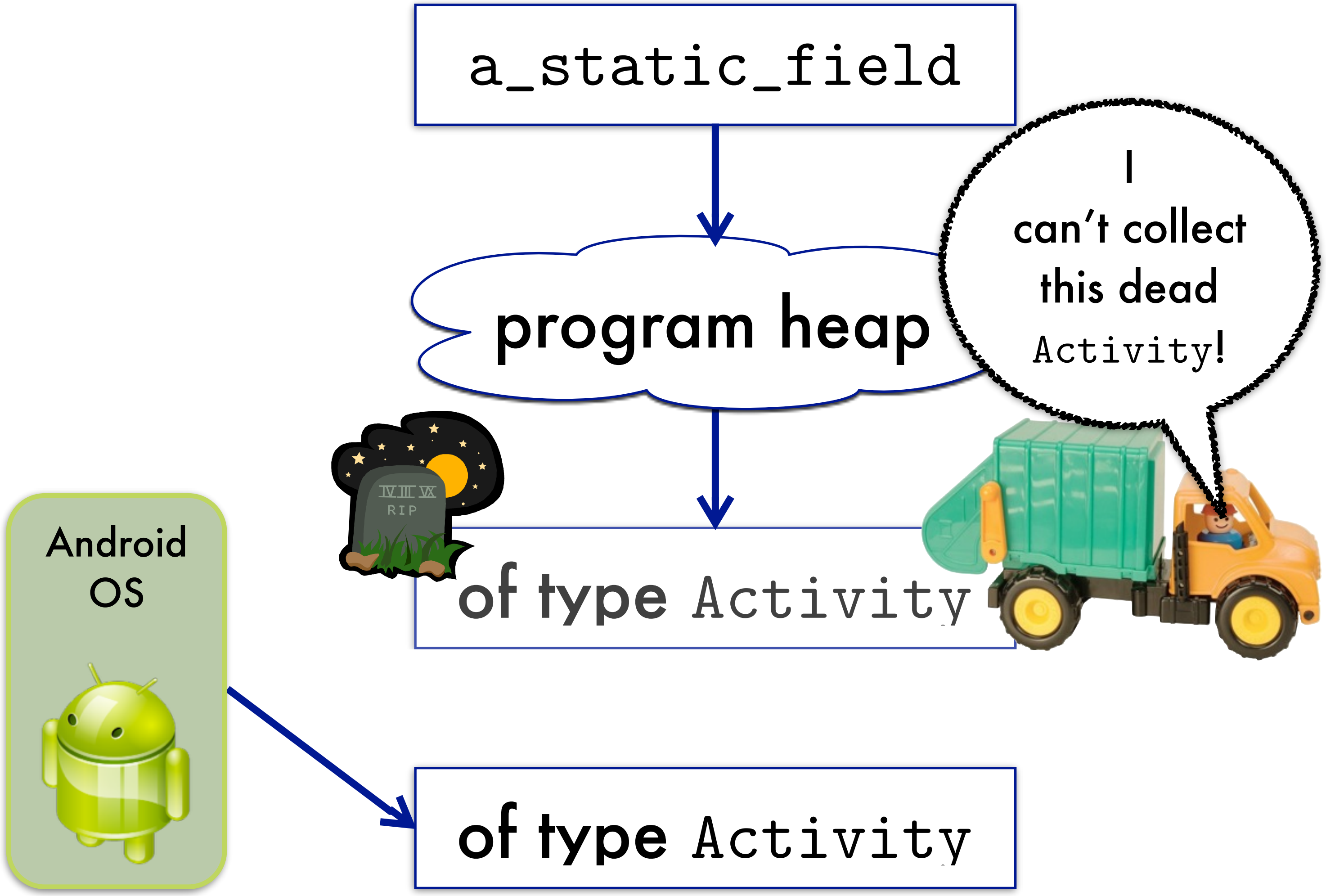

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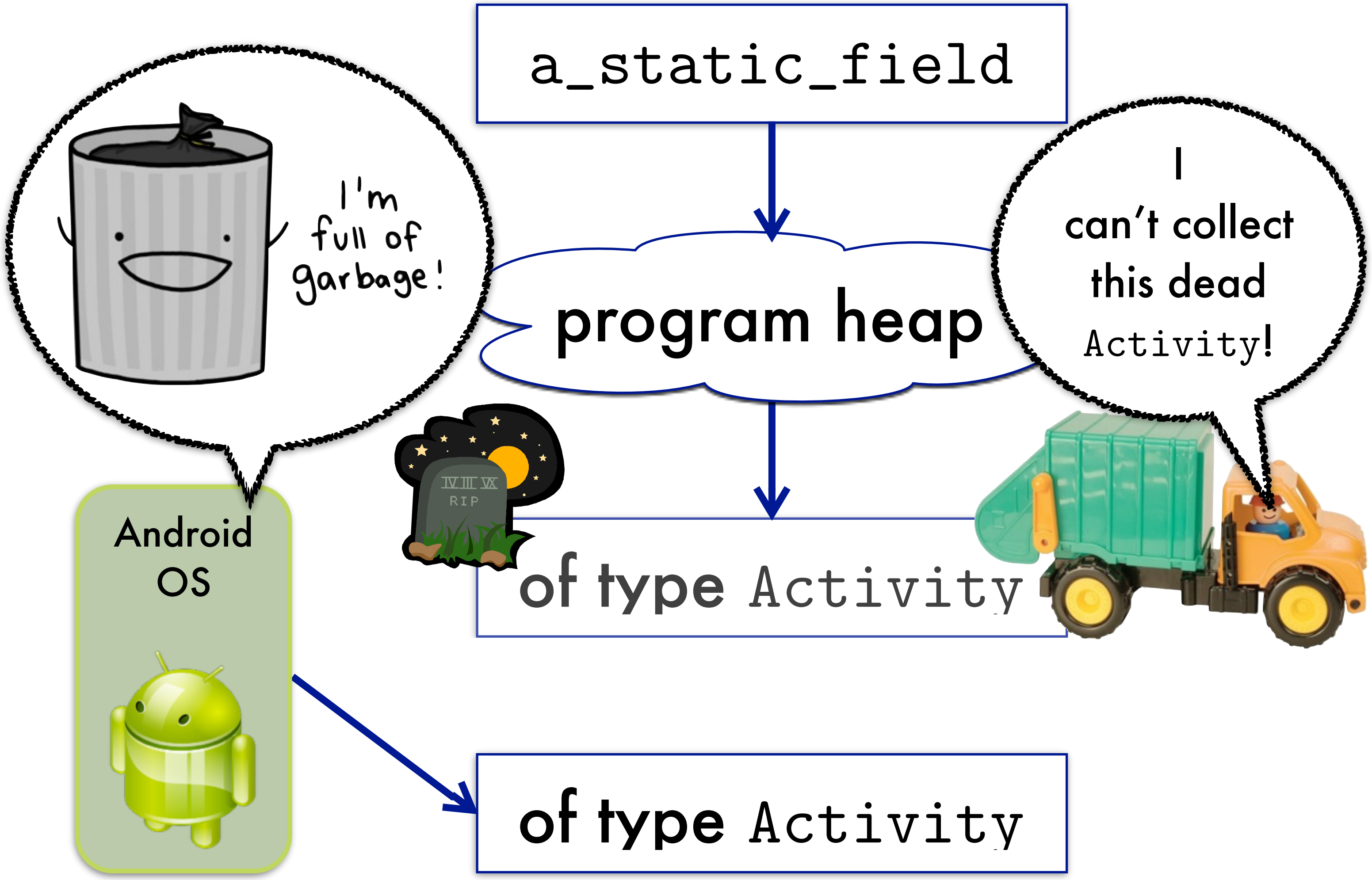

a_static_field

program heap

of type Activity

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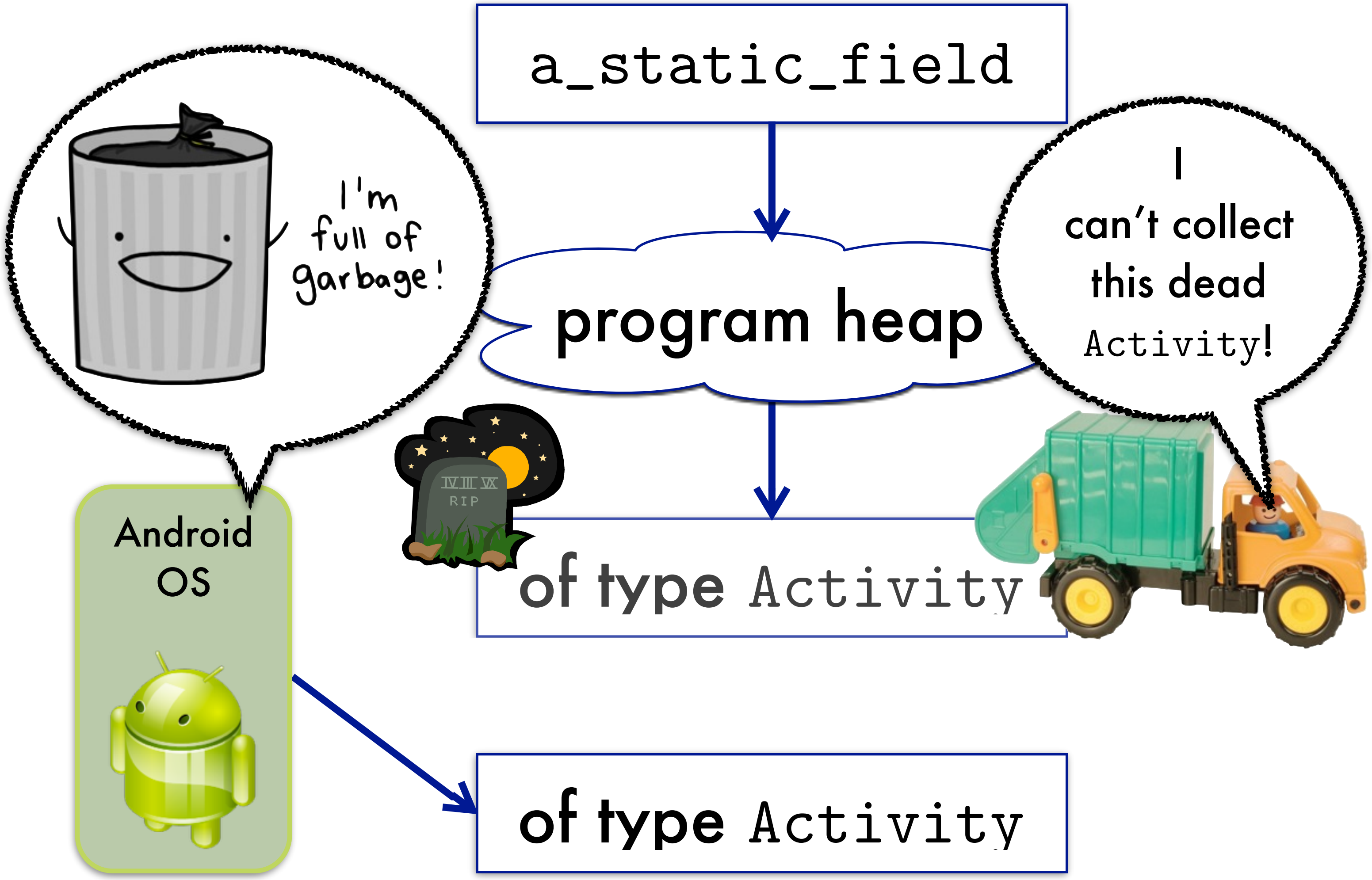

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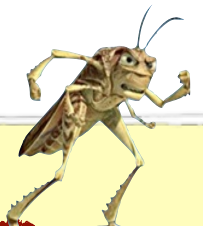

Bug: Holding reference to "old" Activity

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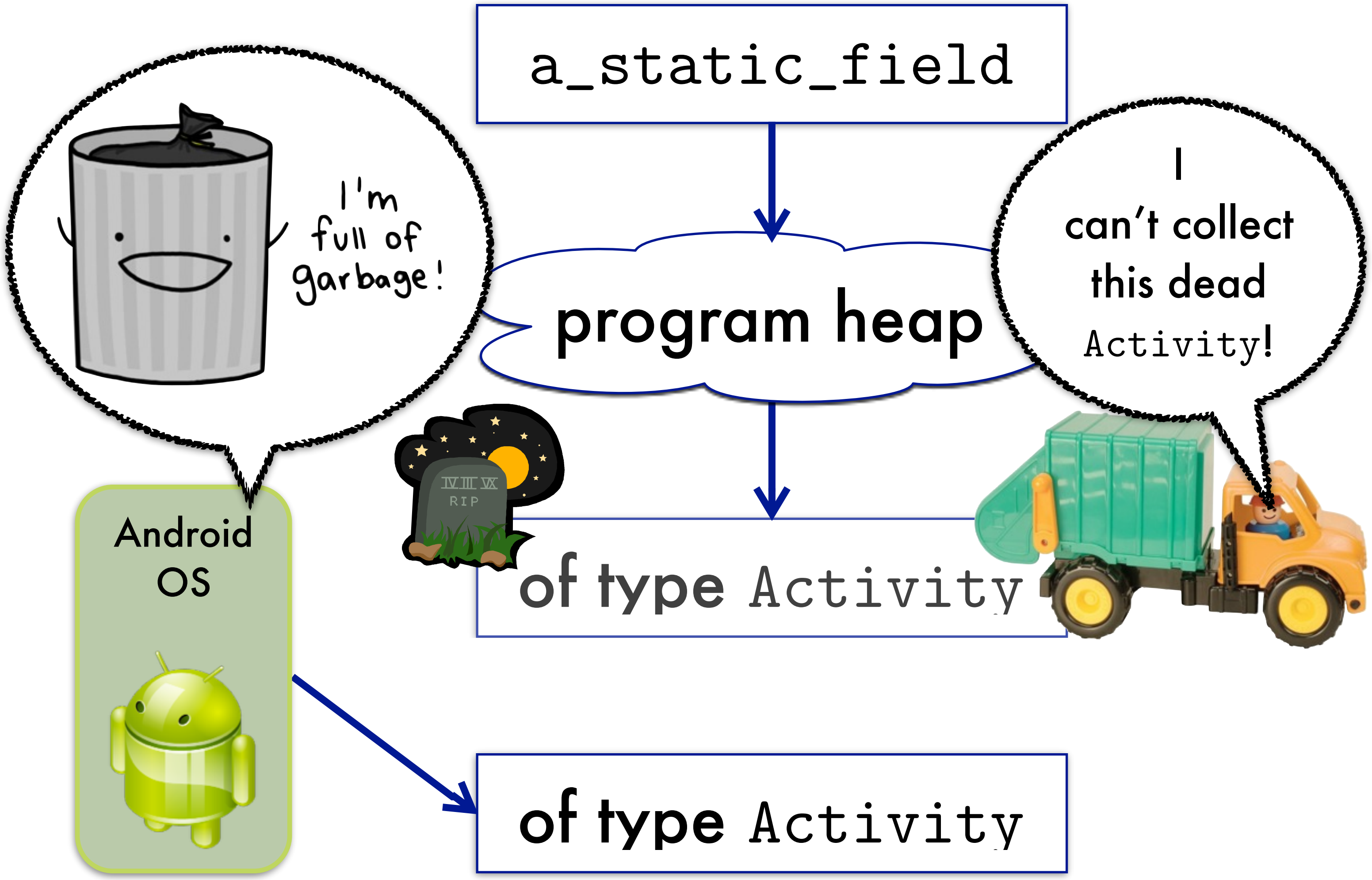

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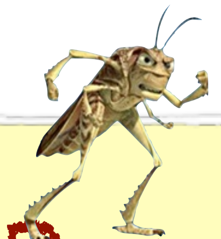
"an Activity leak"



Bug: Holding reference to "old" Activity

The expert recommendation ...

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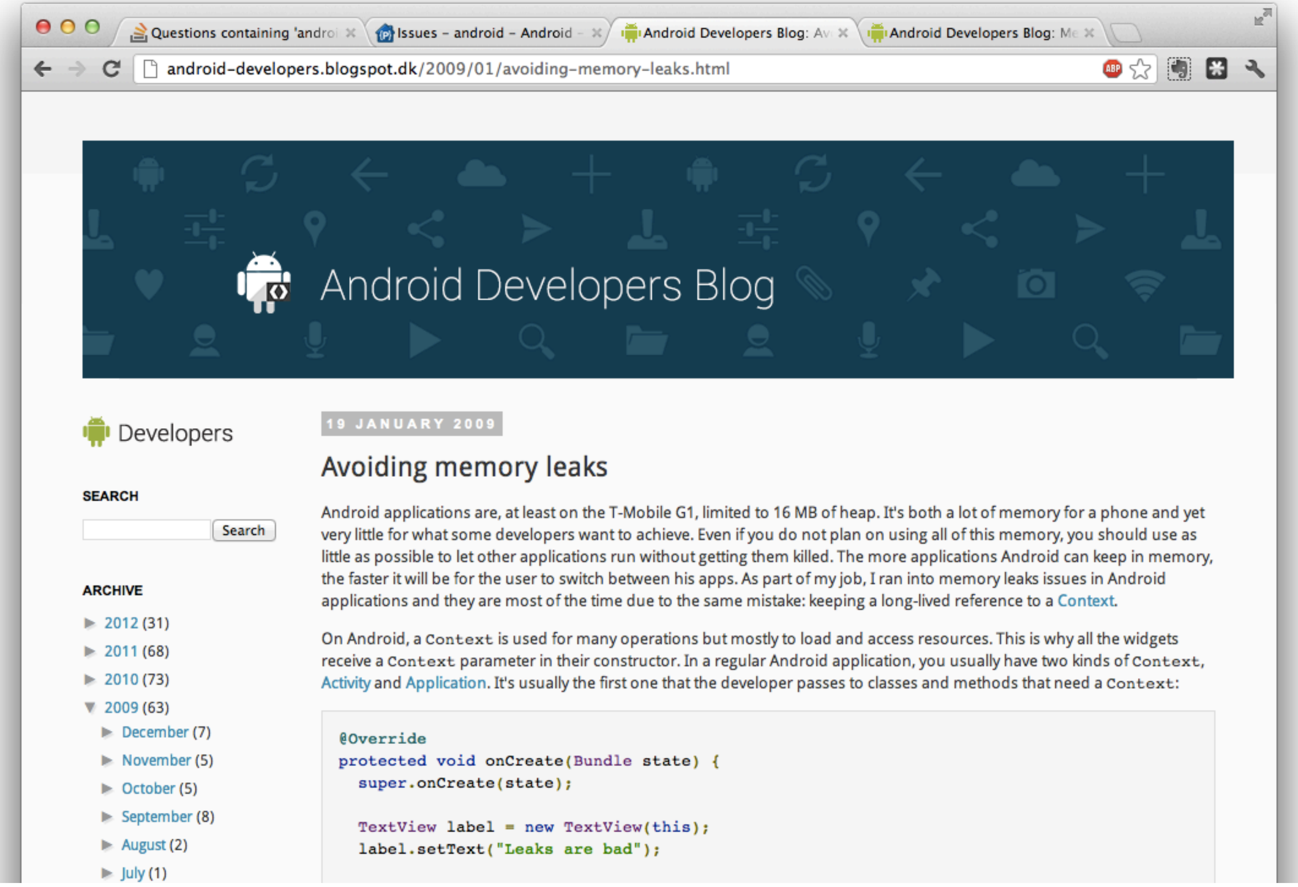
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19 JANUARY 2009

Avoiding memory leaks

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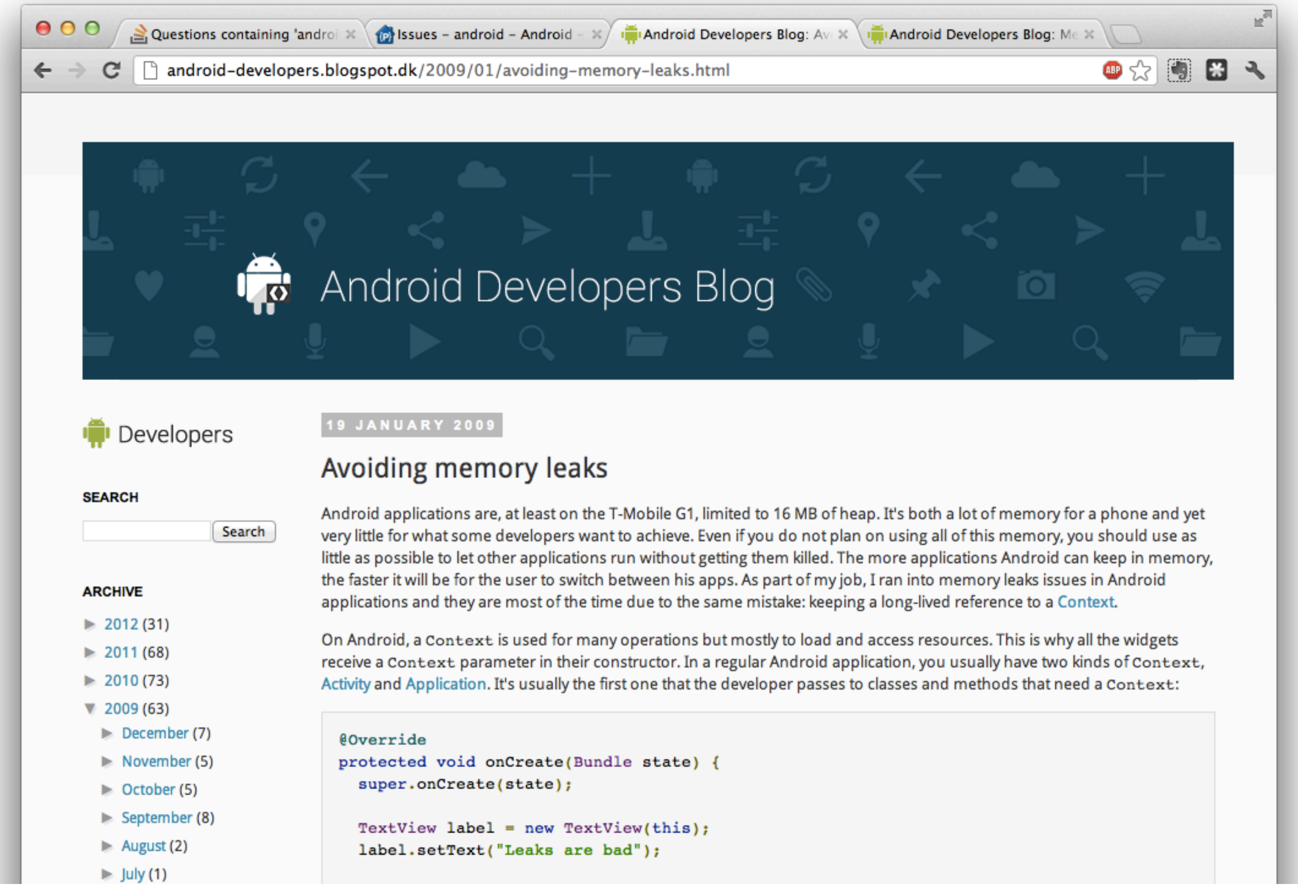
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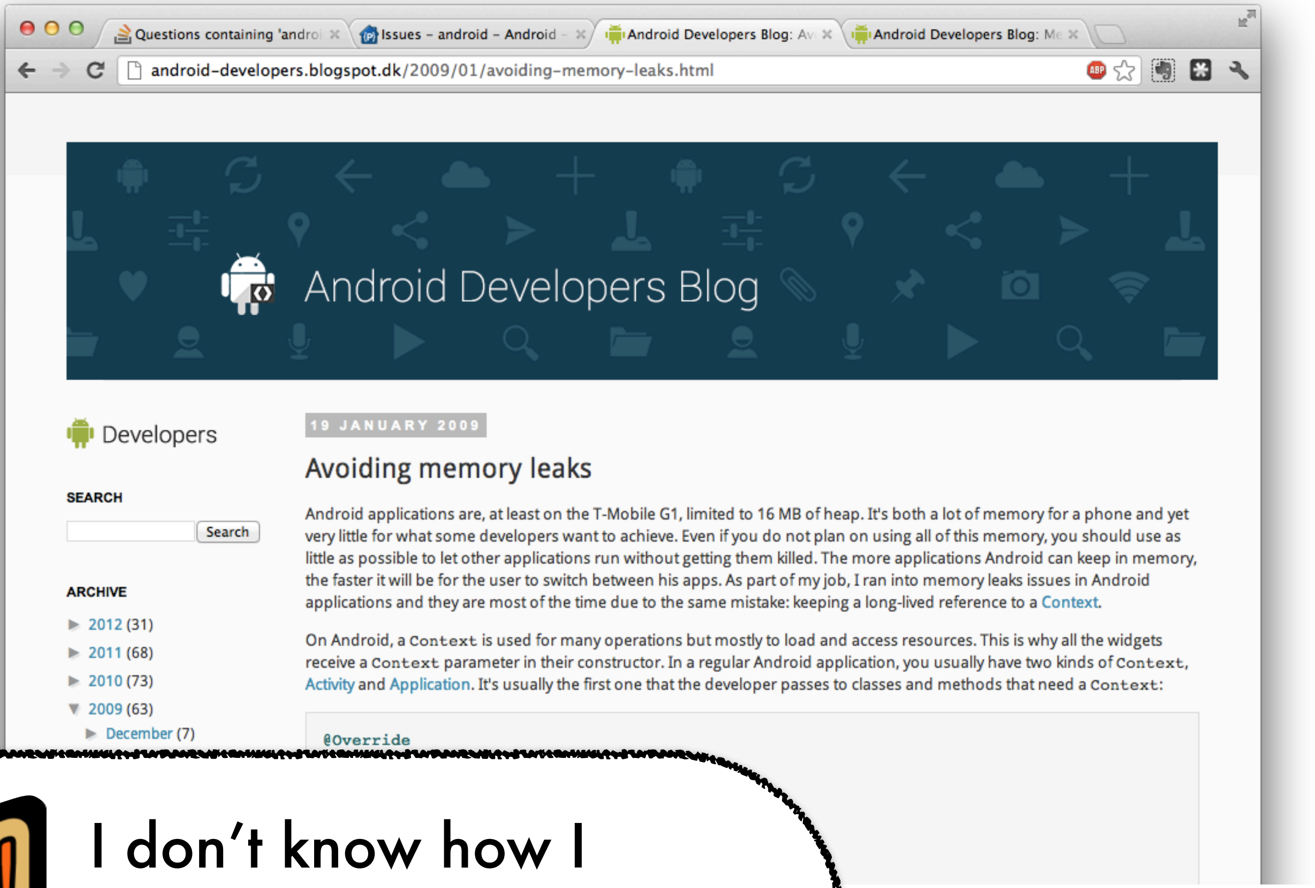

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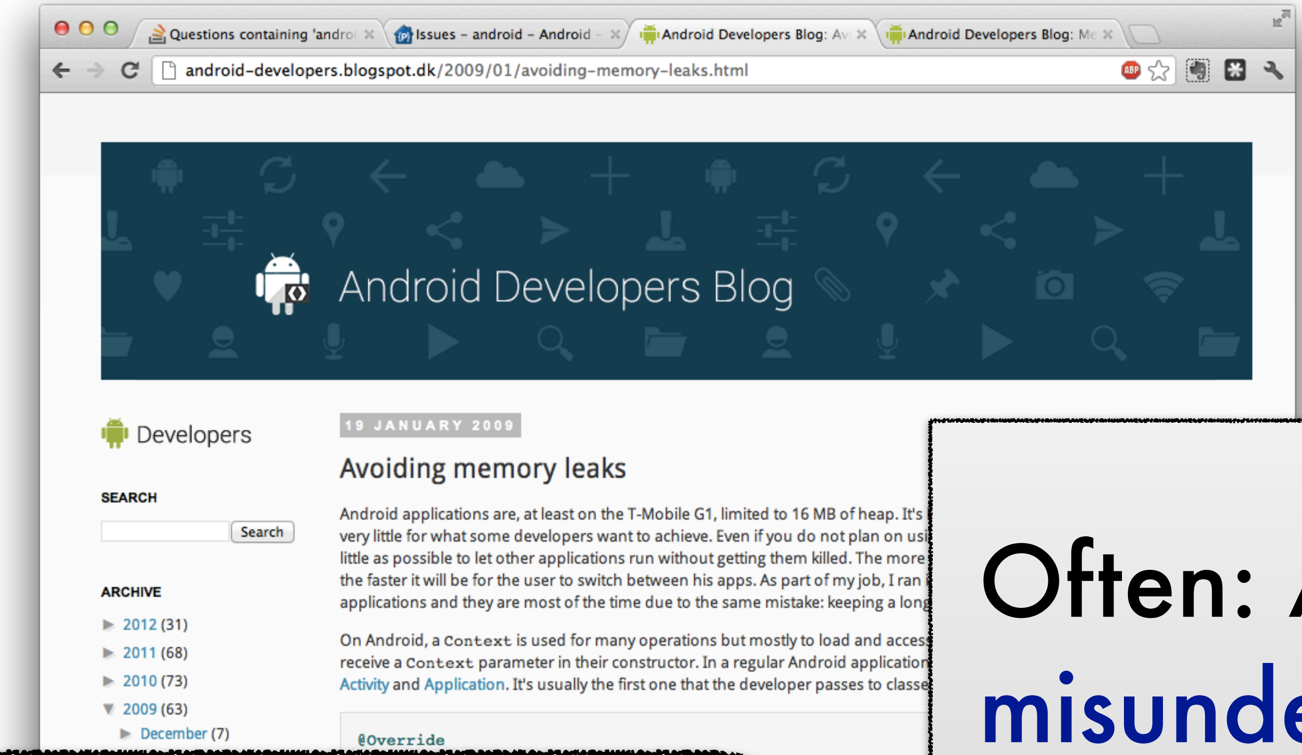

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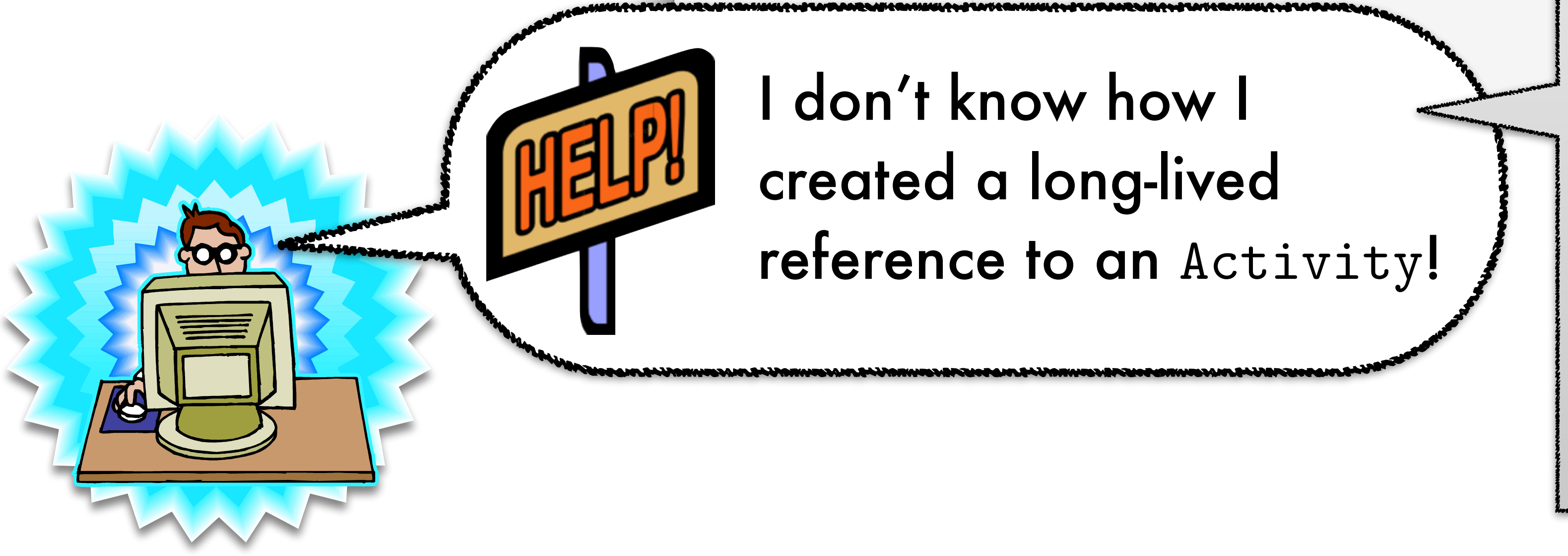

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Often: A **misunderstanding** of a library causes the **library** to keep the `Activity` reference.

VMCAI

The expert recommendation ...

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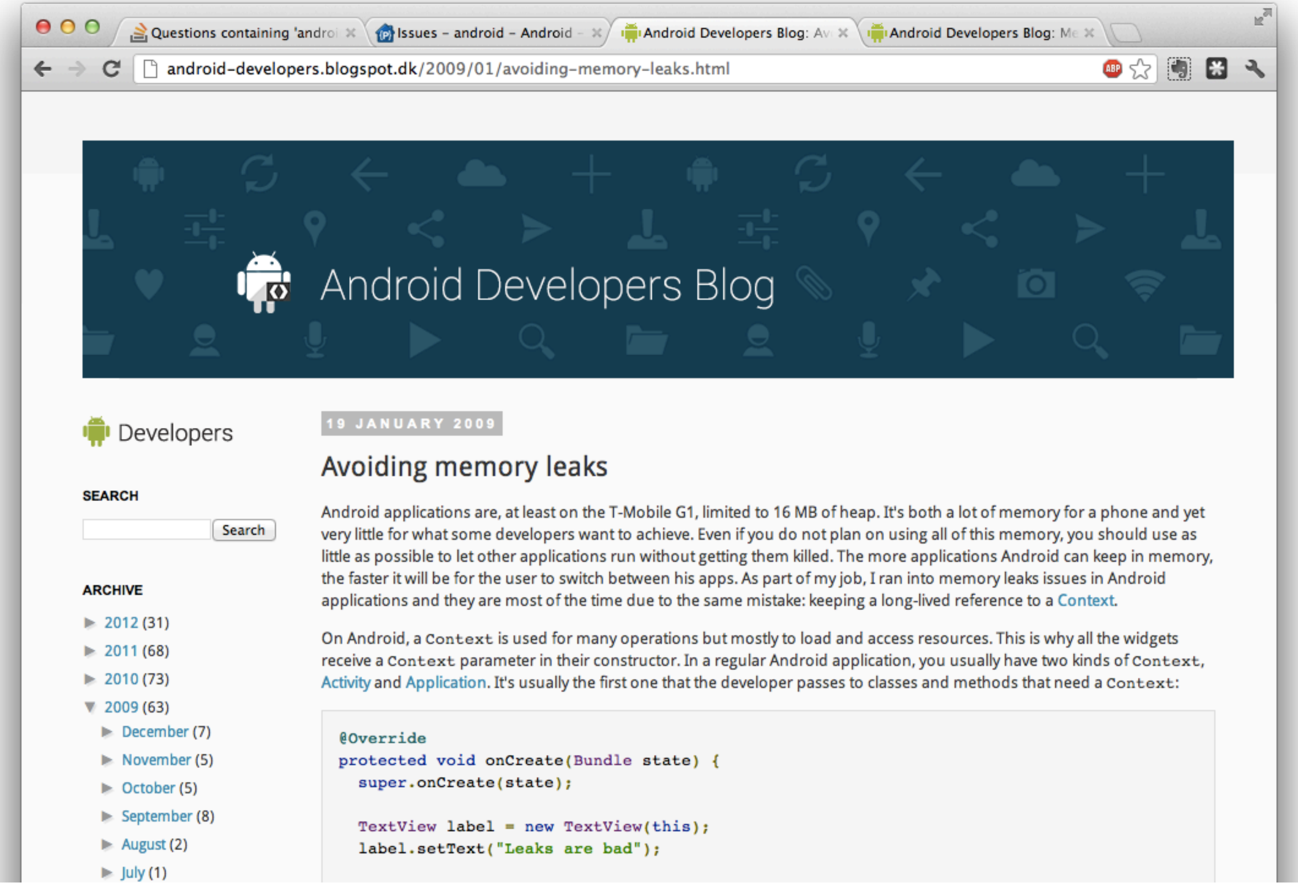
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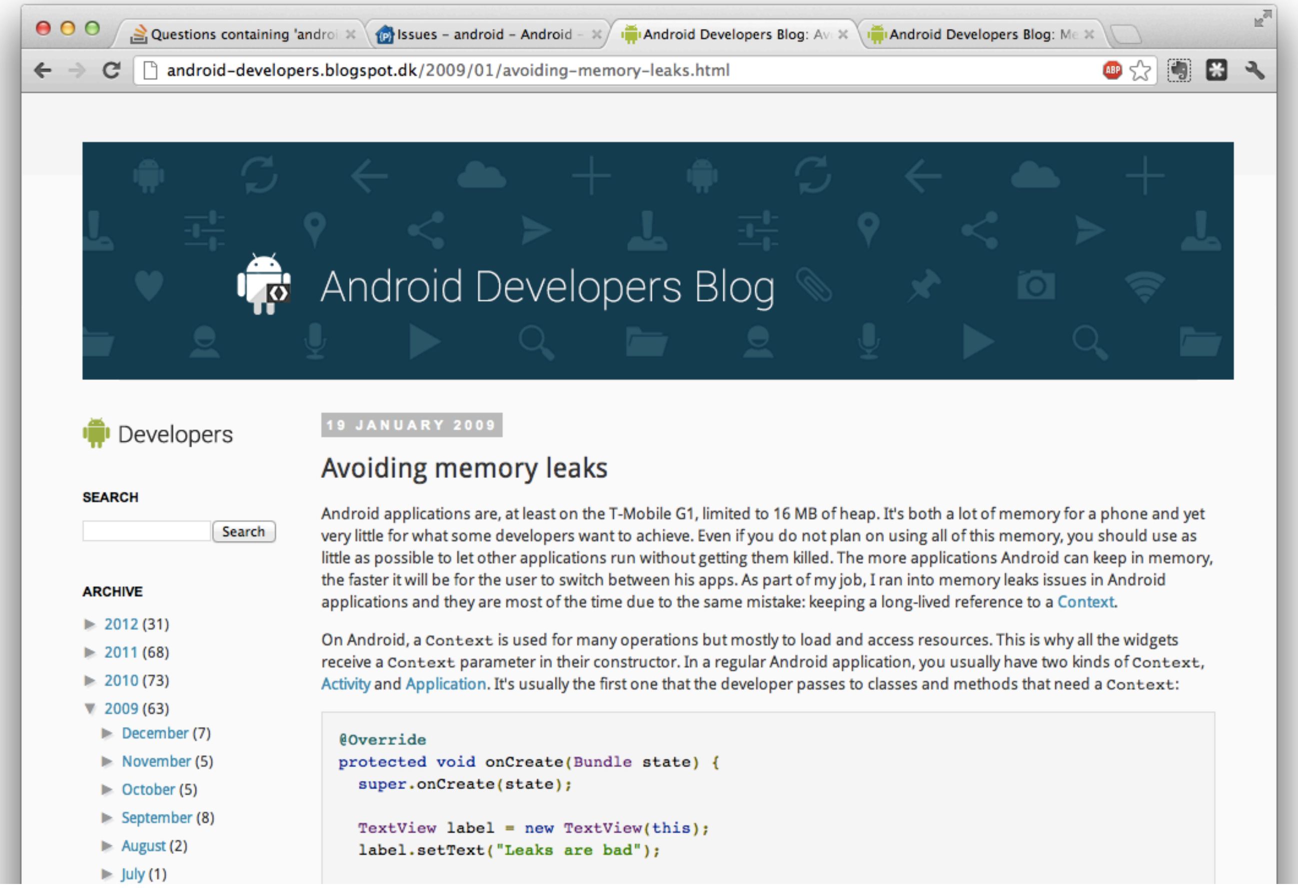
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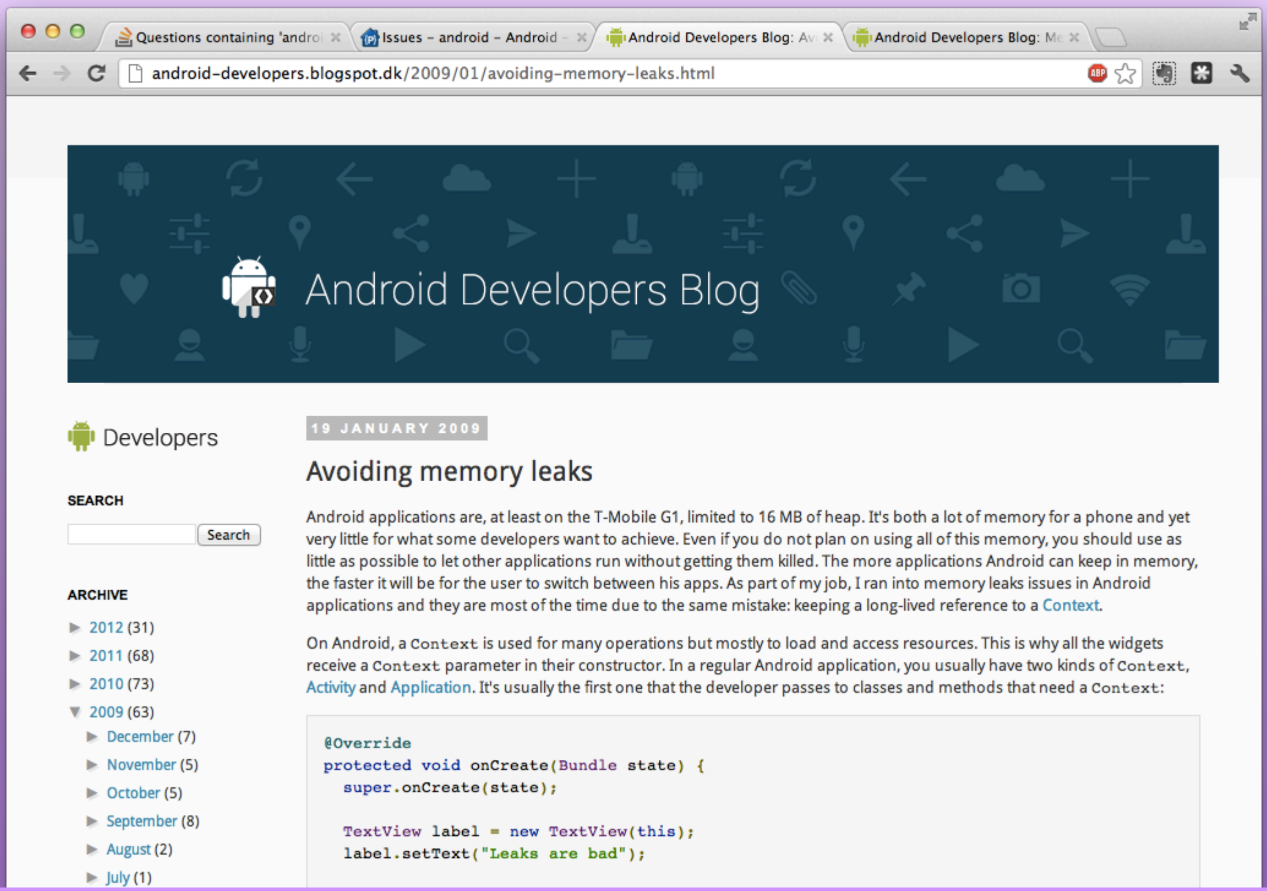

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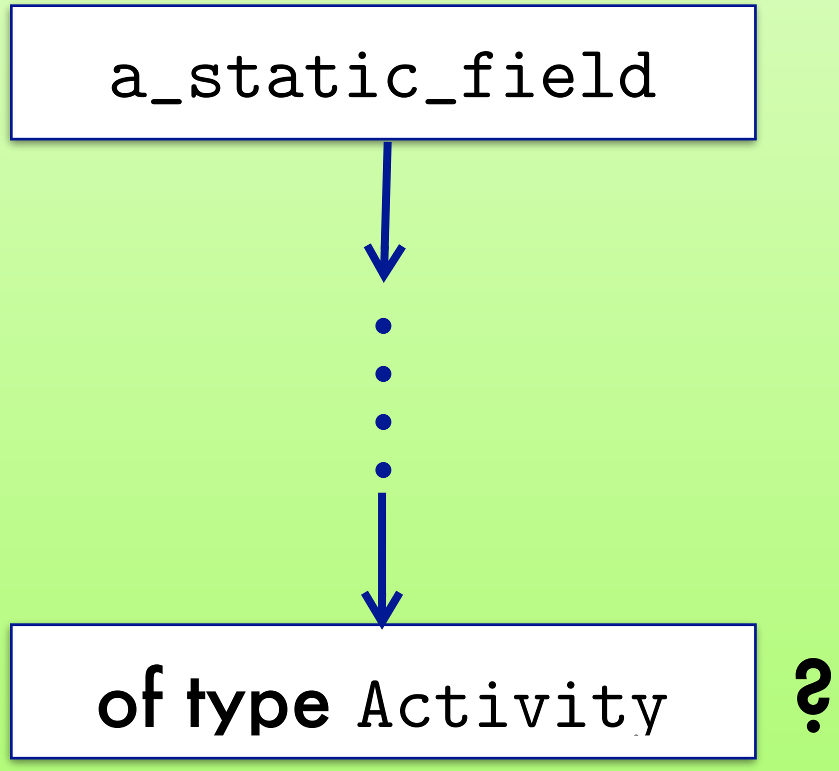
A Specific Property to Check:

No `Activity` is ever reachable from a static field.

A candidate for statically answering, “Is there an `Activity` leak?”

Is there a program execution where at some time



`a_static_field`

of type `Activity`

?

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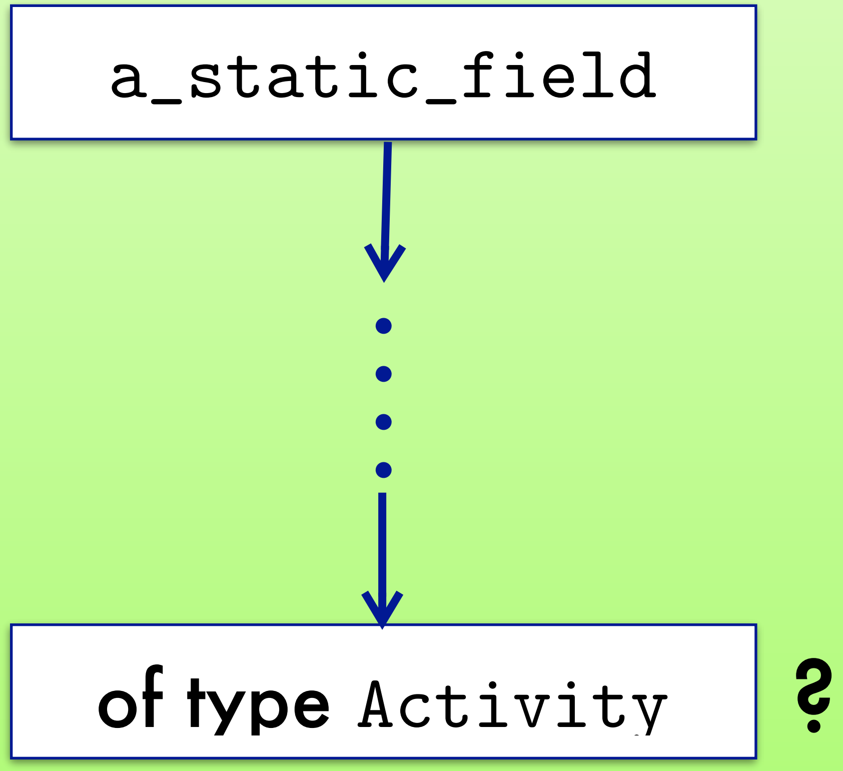

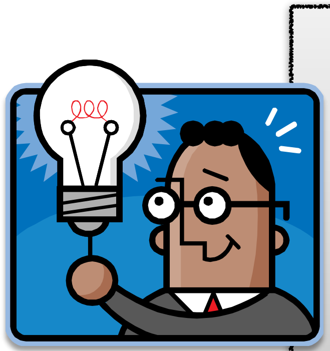

Can be answered with a **points-to analysis**

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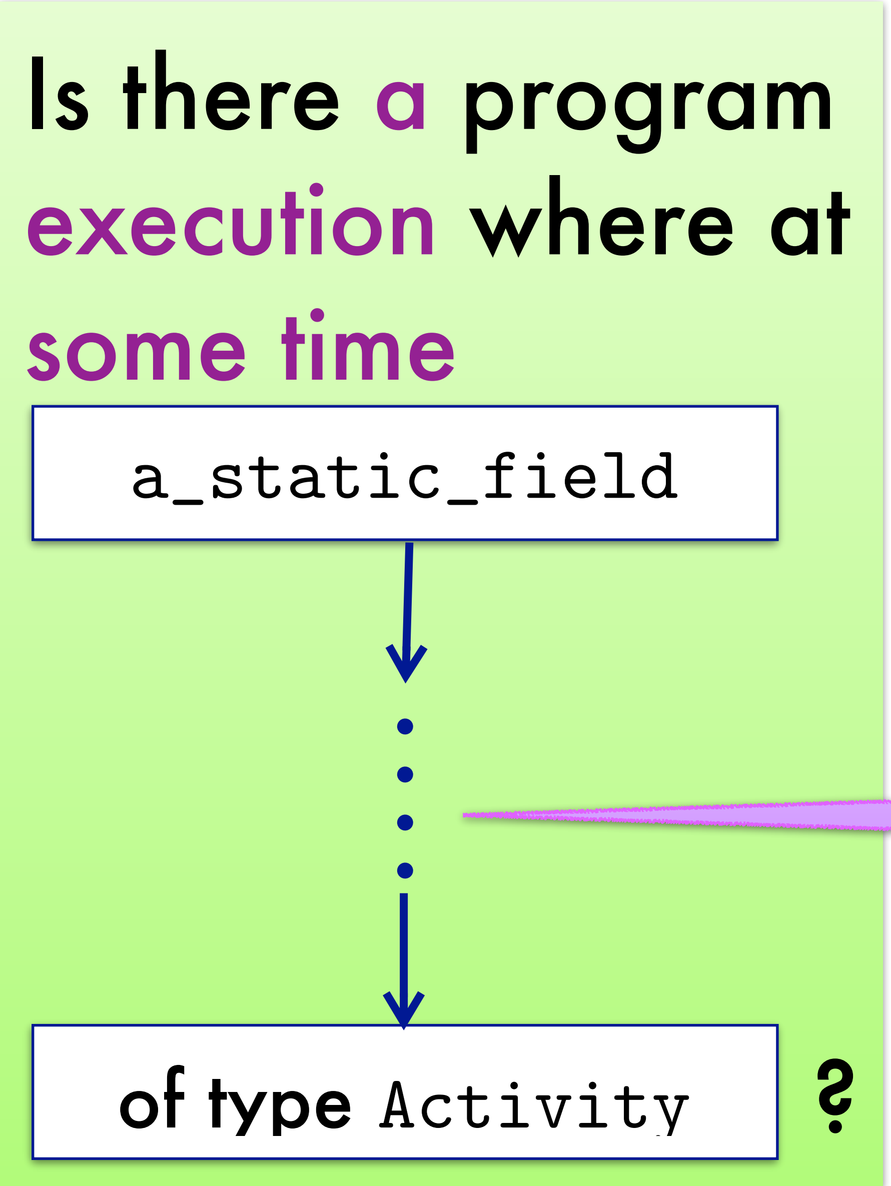

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`a_static_field`

⋮

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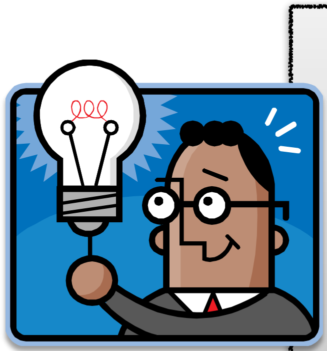

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Compute a points-to graph and look for such points-to paths

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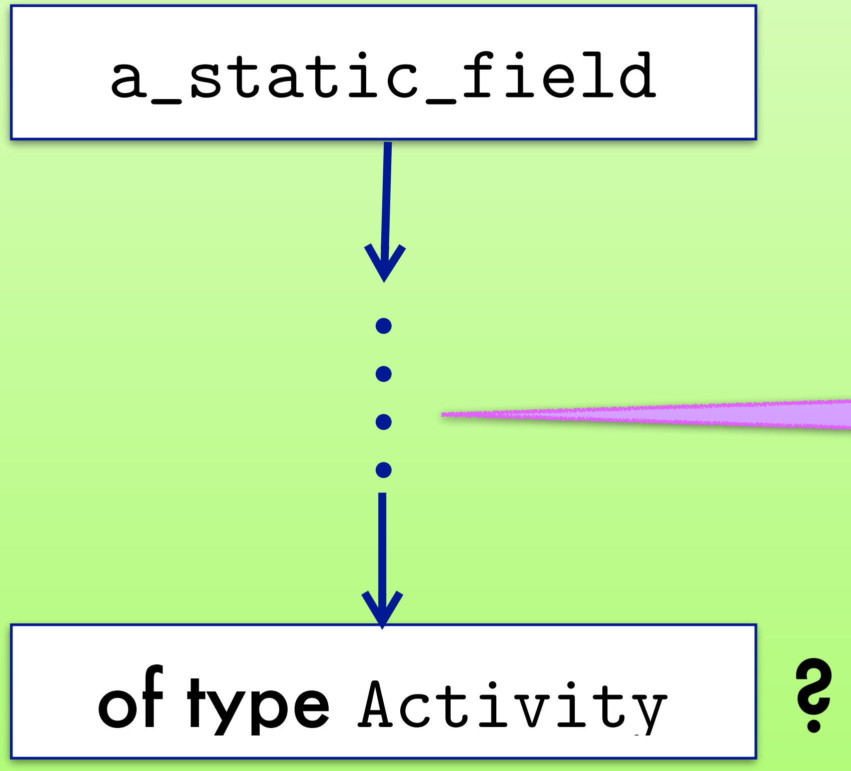

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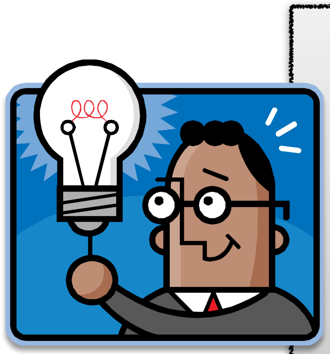

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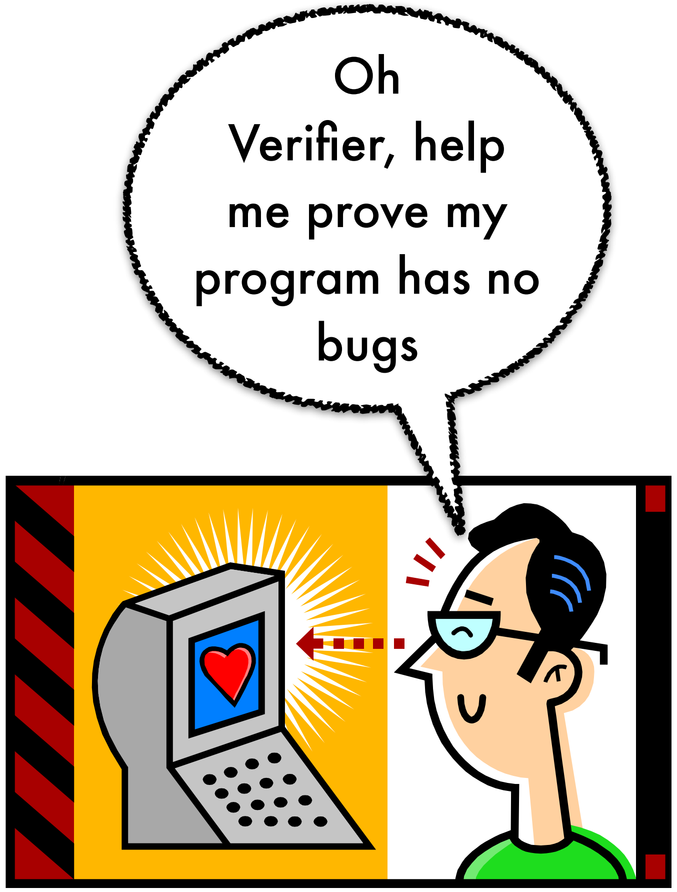
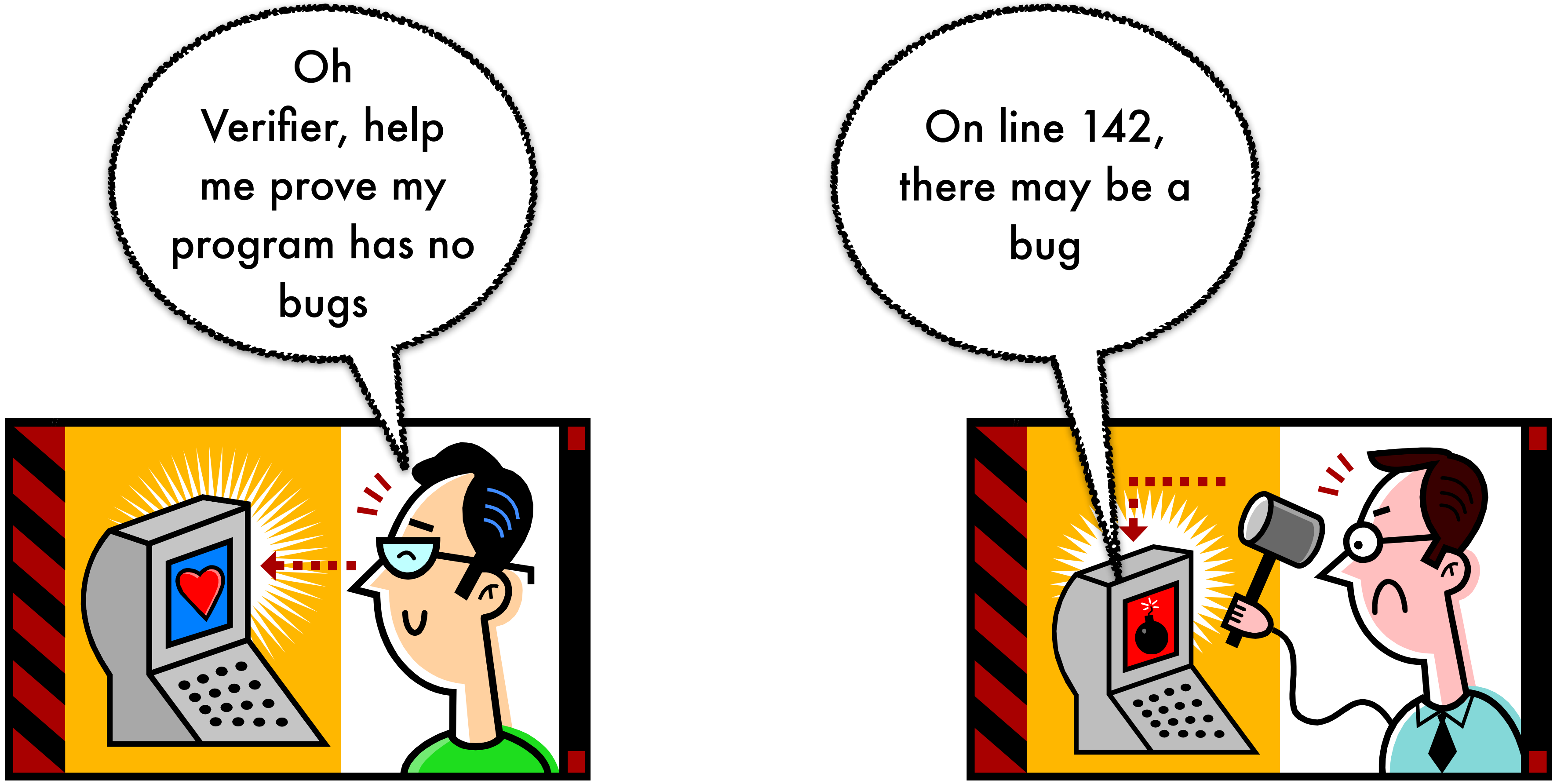
This won’t work because …

The well-known false alarm problem!

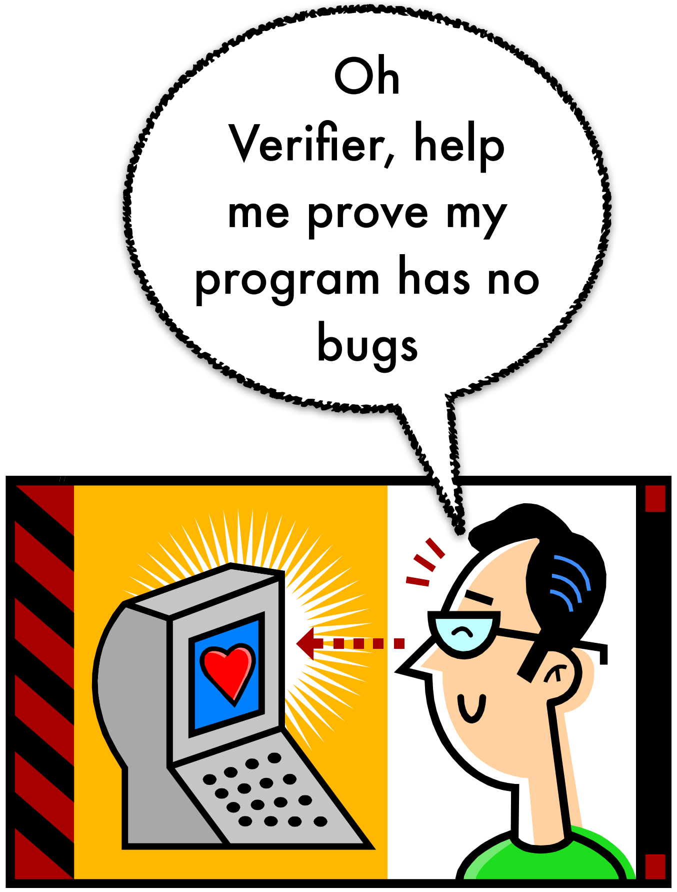
The well-known false alarm problem!

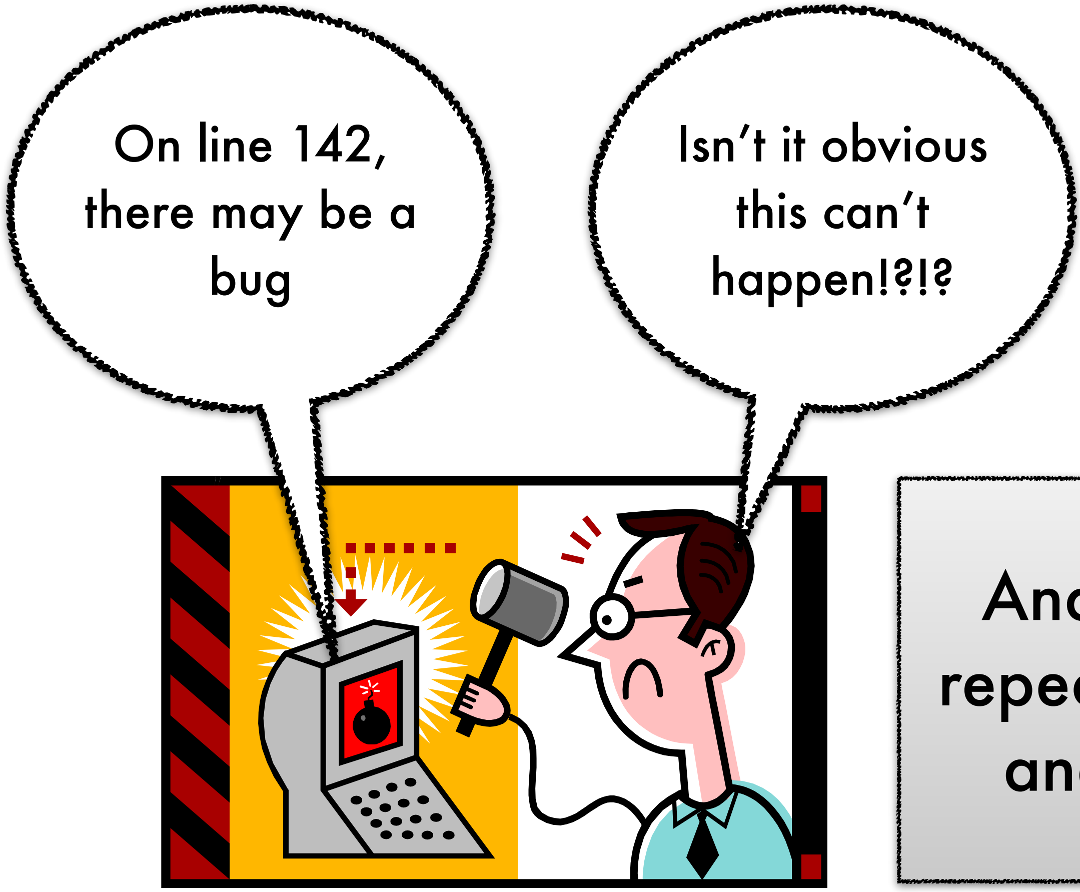


The well-known false alarm problem!


Oh Verifier, help me prove my program has no bugs
On line 142, there may be a bug

The well-known false alarm problem!




On line 142, there may be a bug
Isn’t it obvious this can’t happen!?!?

And noisily repeated over and over!

The well-known false alarm problem!

Oh
Verifie
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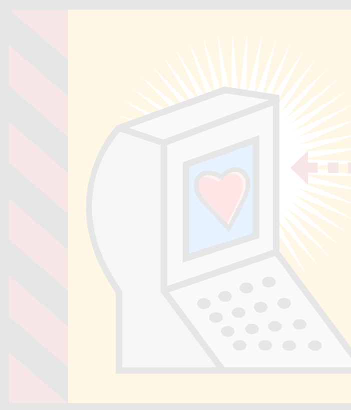

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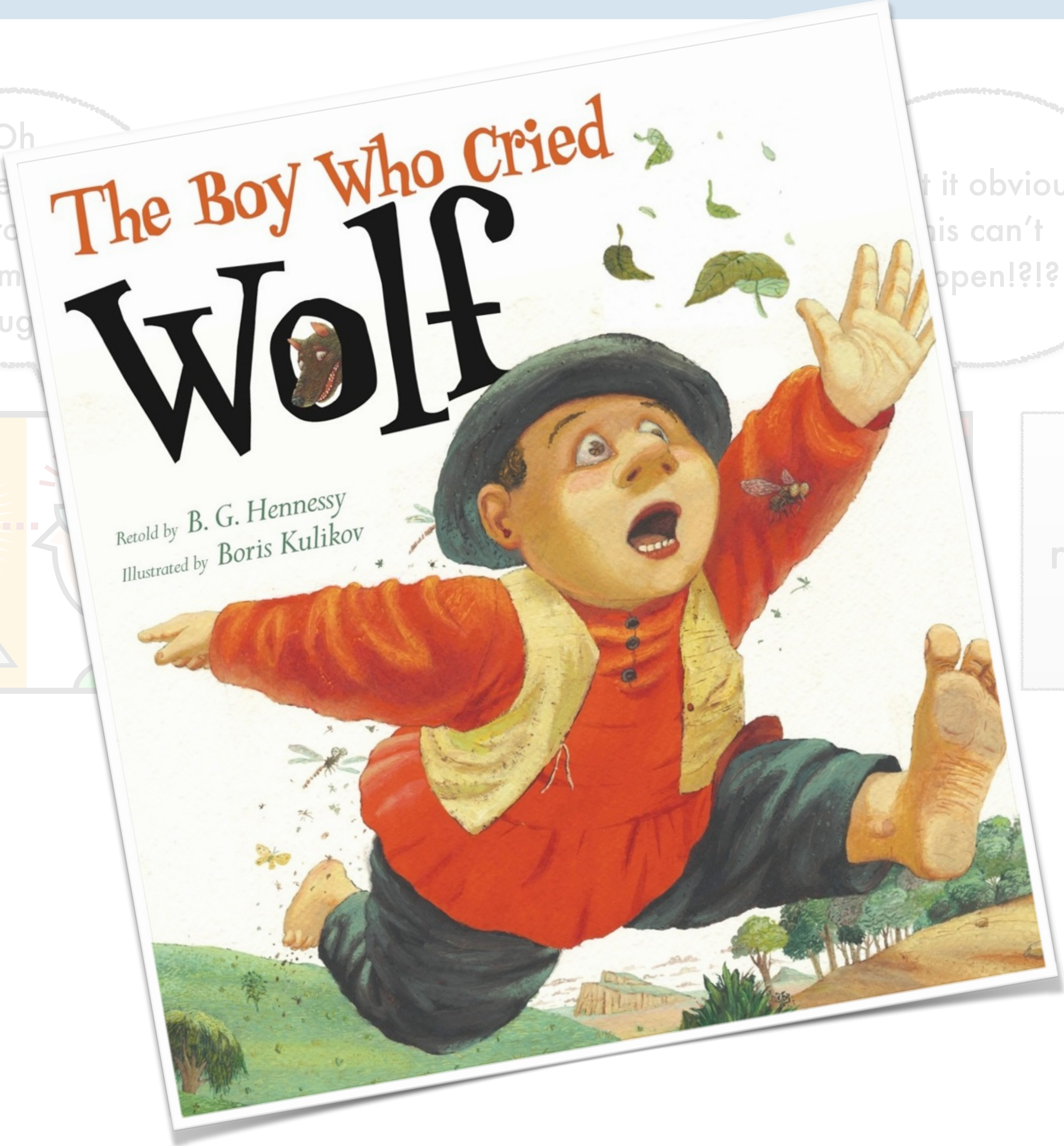

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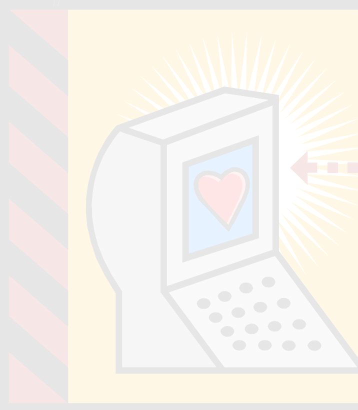

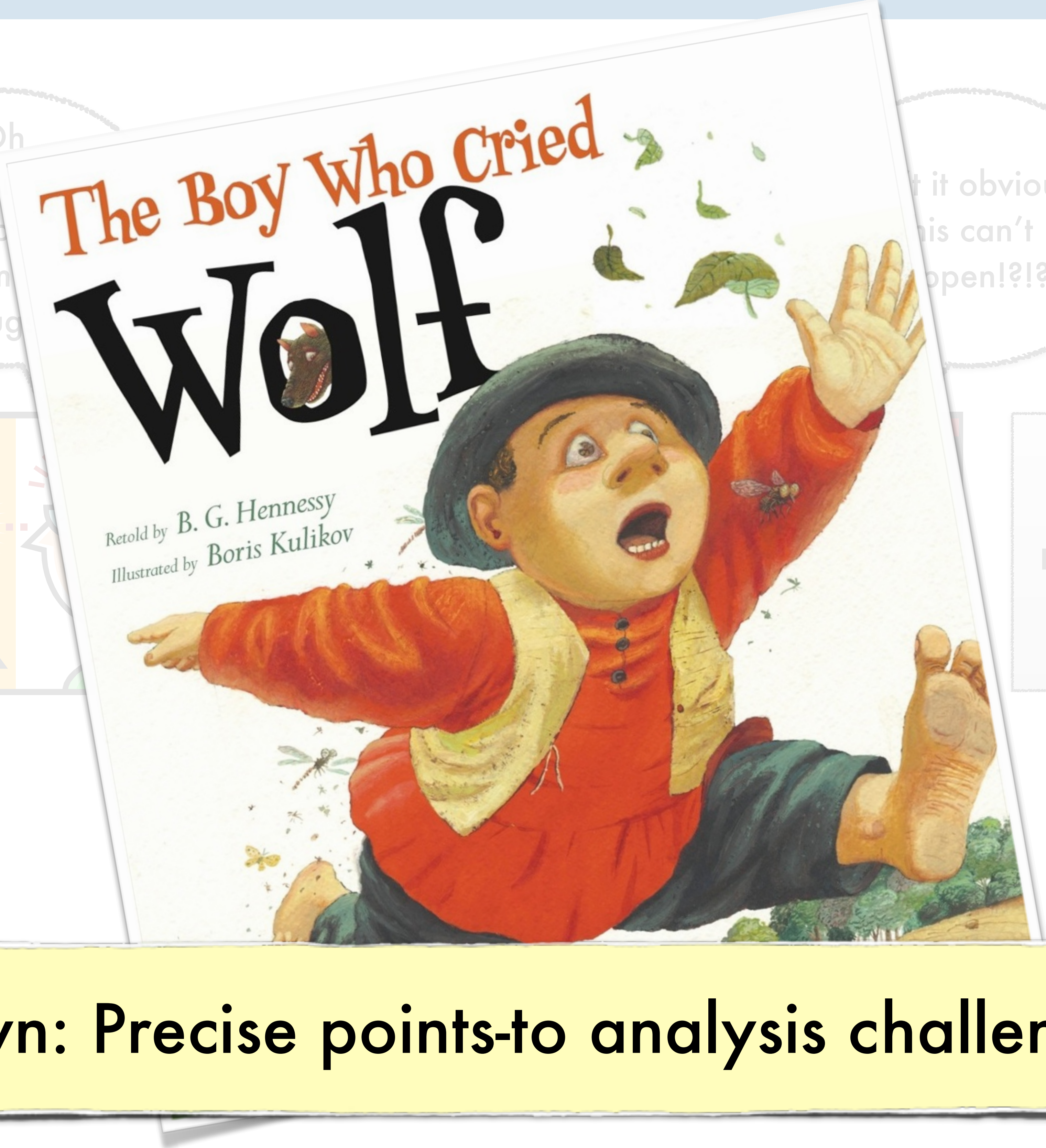

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Known: Precise points-to analysis challenging

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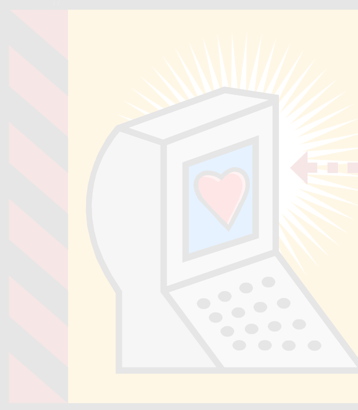

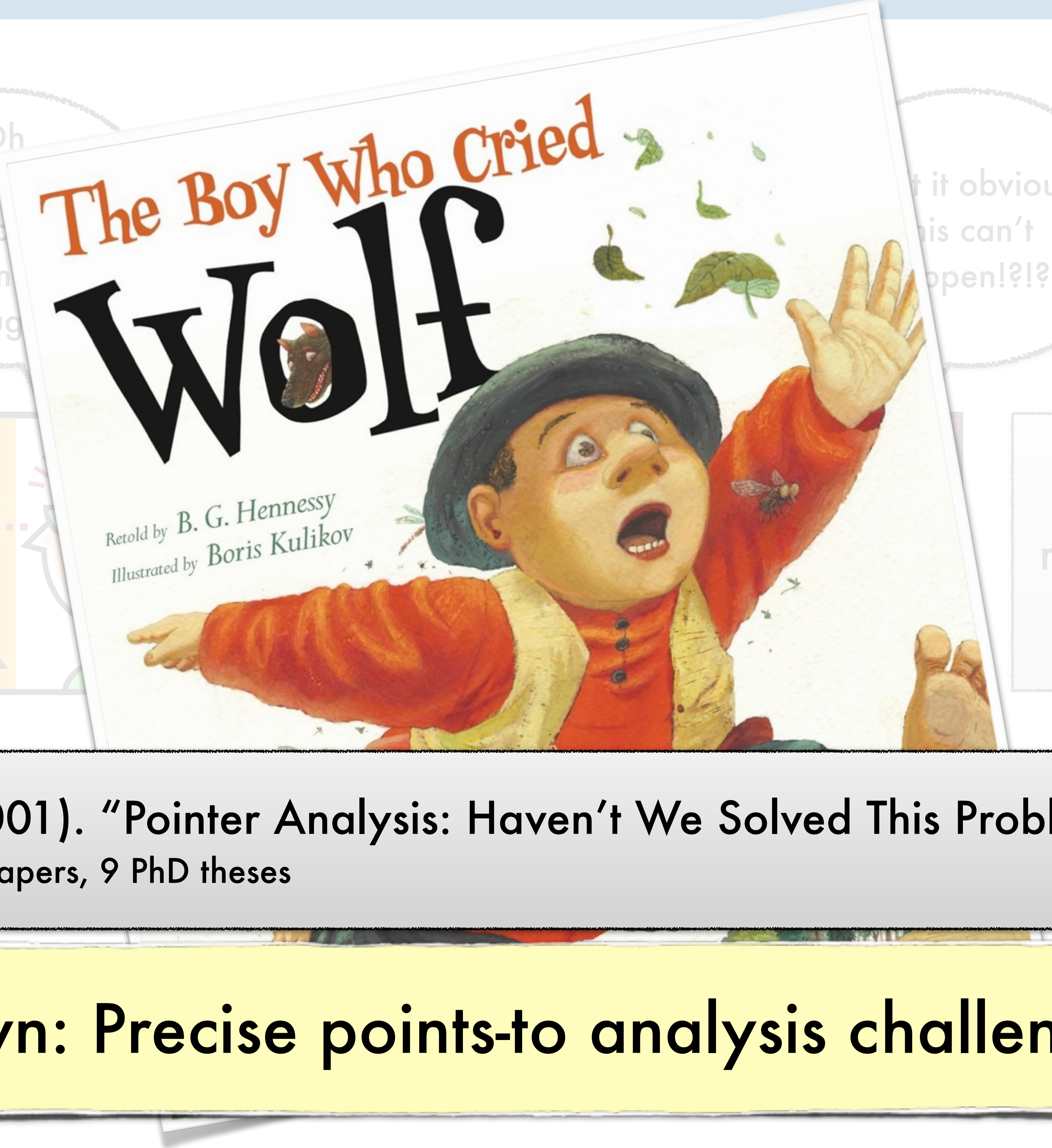

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Hind (2001). "Pointer Analysis: Haven't We Solved This Problem Yet?"

- 75 papers, 9 PhD theses

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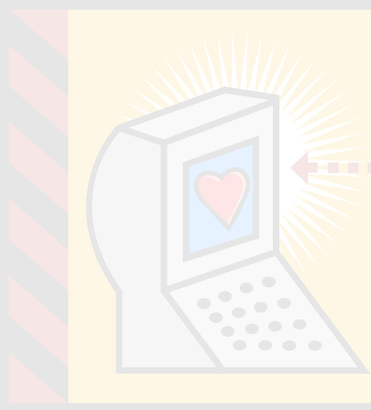
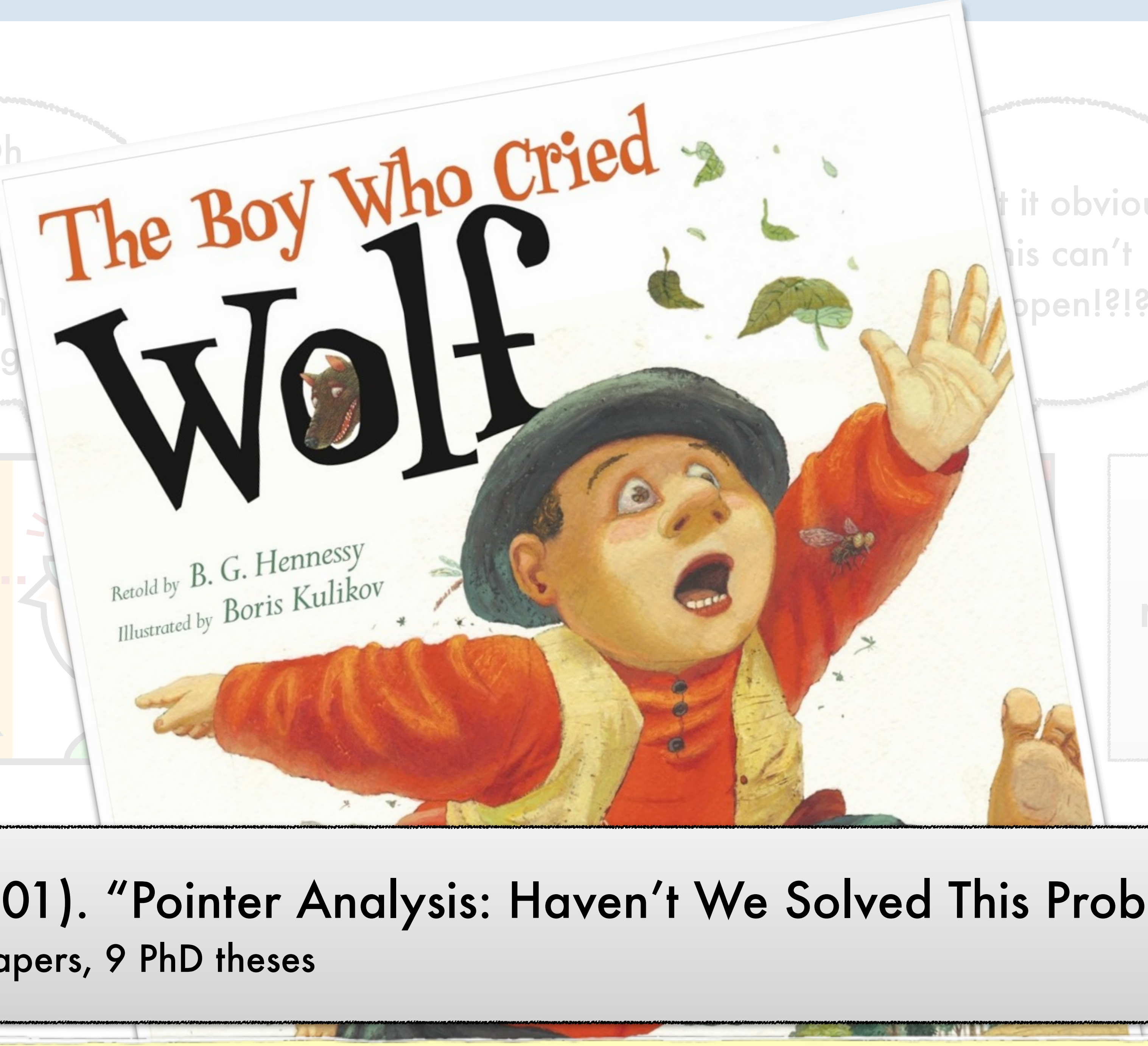




And noisily repeated over and over!

Hind (2001). “Pointer Analysis: Haven't We Solved This Problem Yet?”

- 75 papers, 9 PhD theses

Known: Precise ^enough points-to analysis ~~challenging~~ impossible?

VMCAI

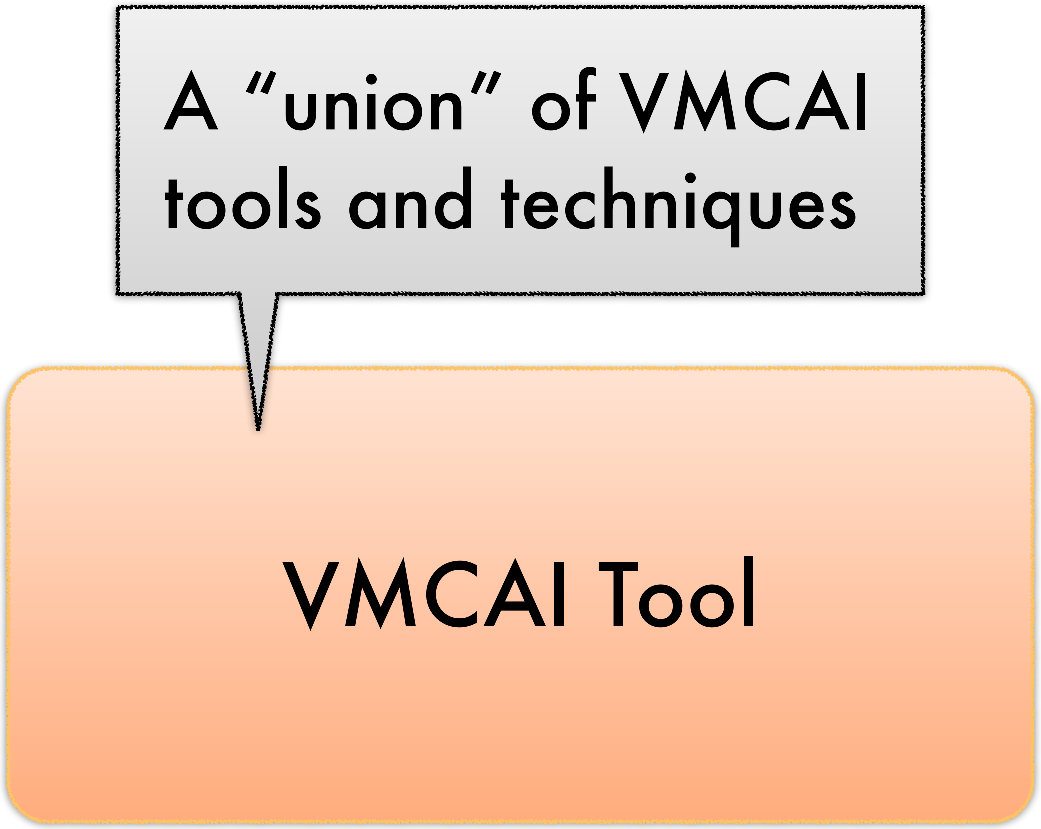
Next: A perspective on VMCAI and false alarms

Perspective: The false alarm problem and VMCAI

Perspective: The false alarm problem and VMCAI

VMCAI Tool

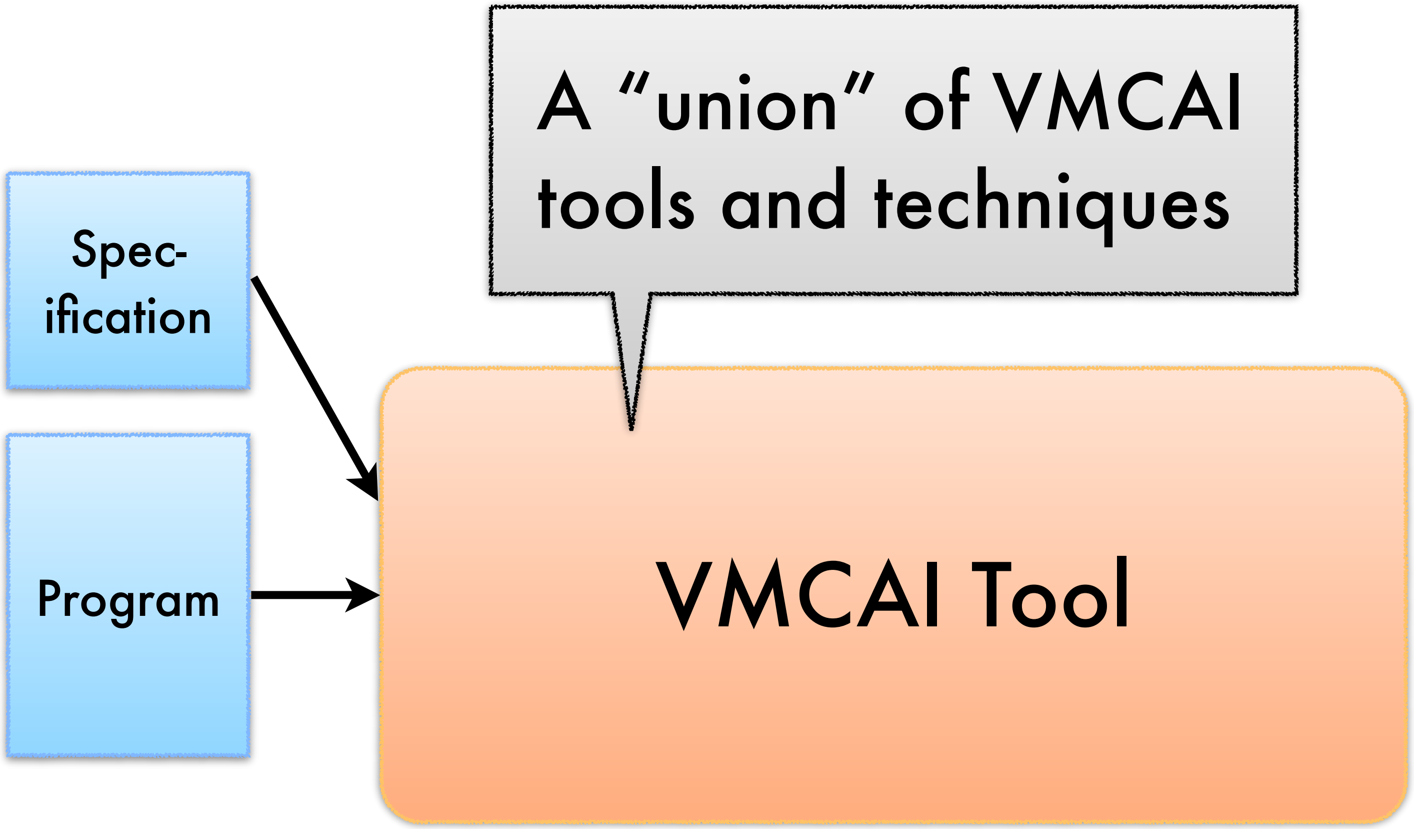
Perspective: The false alarm problem and VMCAI



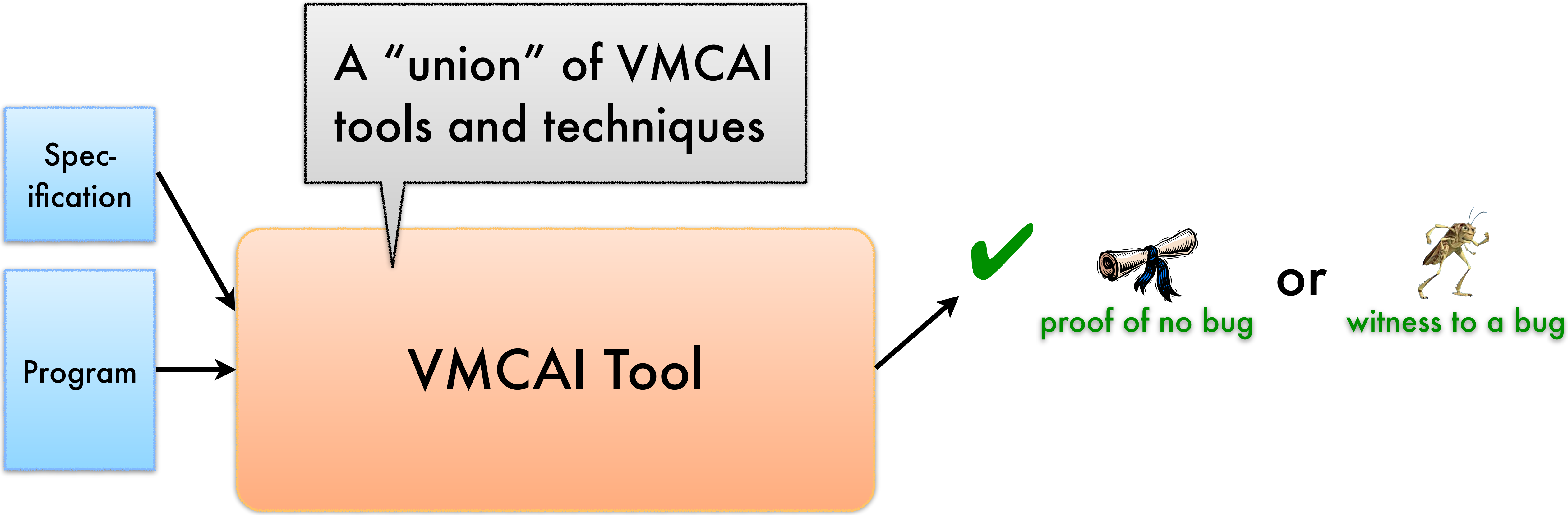
A “union” of VMCAI tools and techniques

VMCAI Tool

Perspective: The false alarm problem and VMCAI



Perspective: The false alarm problem and VMCAI



A “union” of VMCAI tools and techniques

Spec-ification

Program

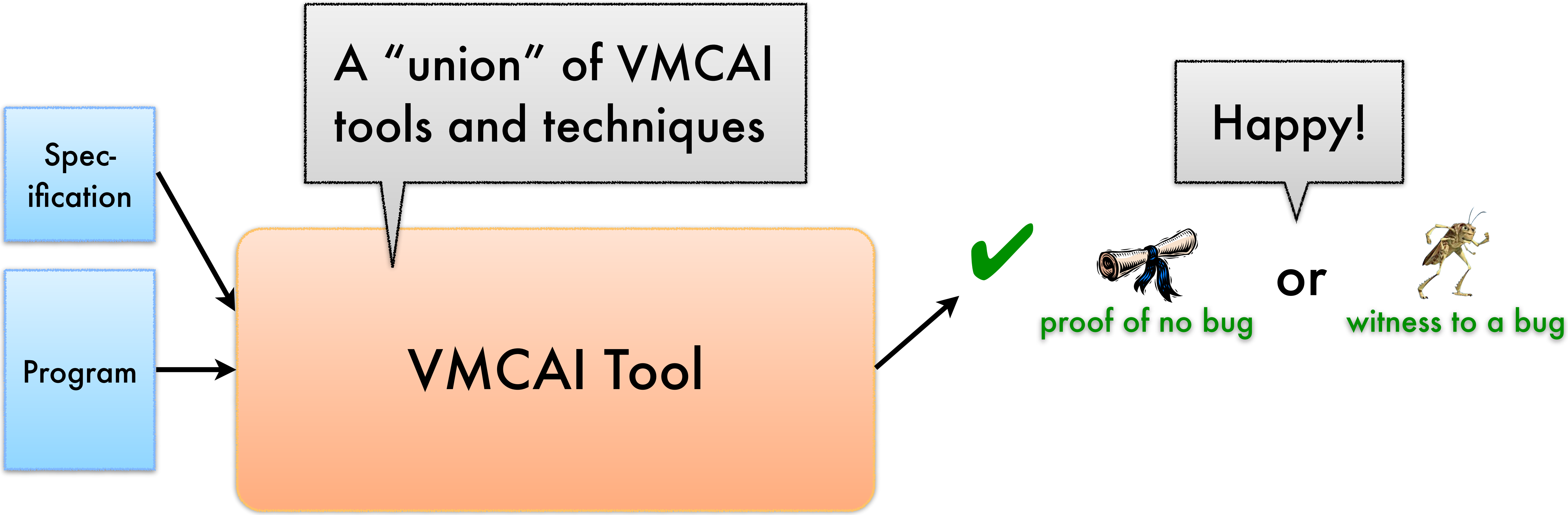
VMCAI Tool

✔ proof of no bug

or

witness to a bug

Perspective: The false alarm problem and VMCAI



Spec-ification

Program

A "union" of VMCAI tools and techniques

VMCAI Tool

✓

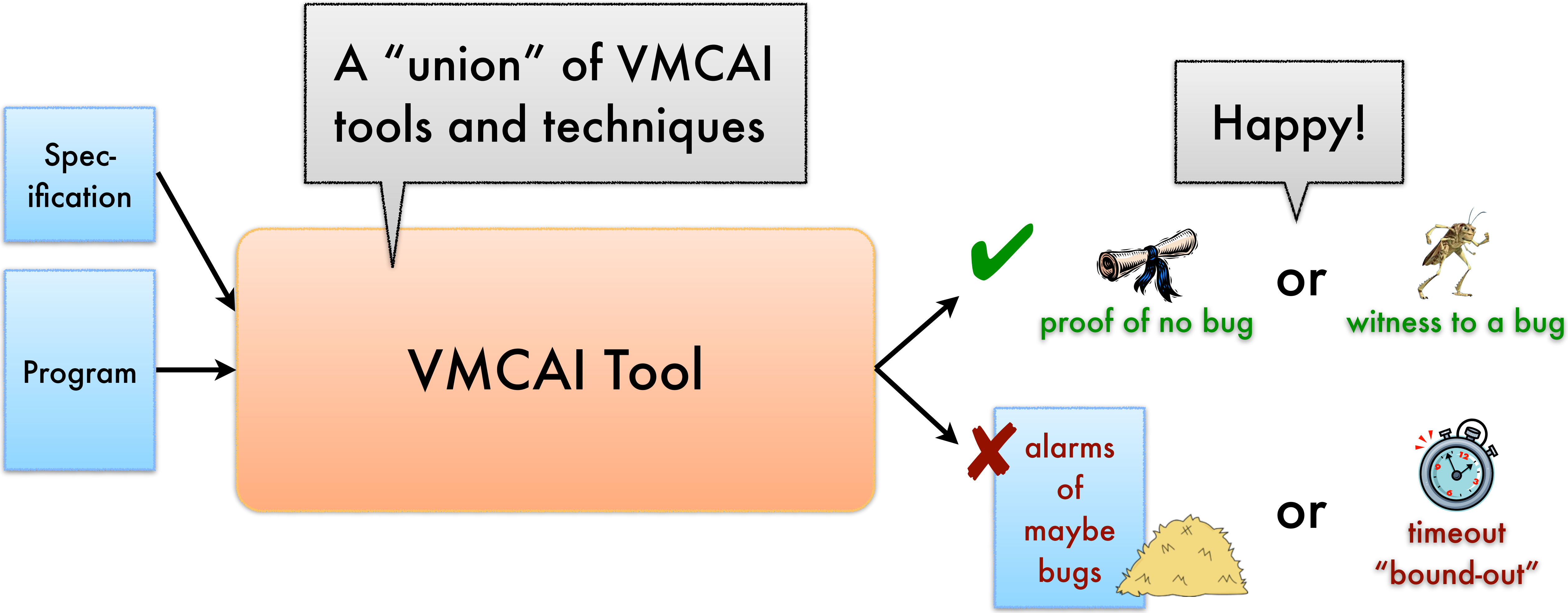
proof of no bug

or

witness to a bug

Happy!

Perspective: The false alarm problem and VMCAI



A "union" of VMCAI tools and techniques

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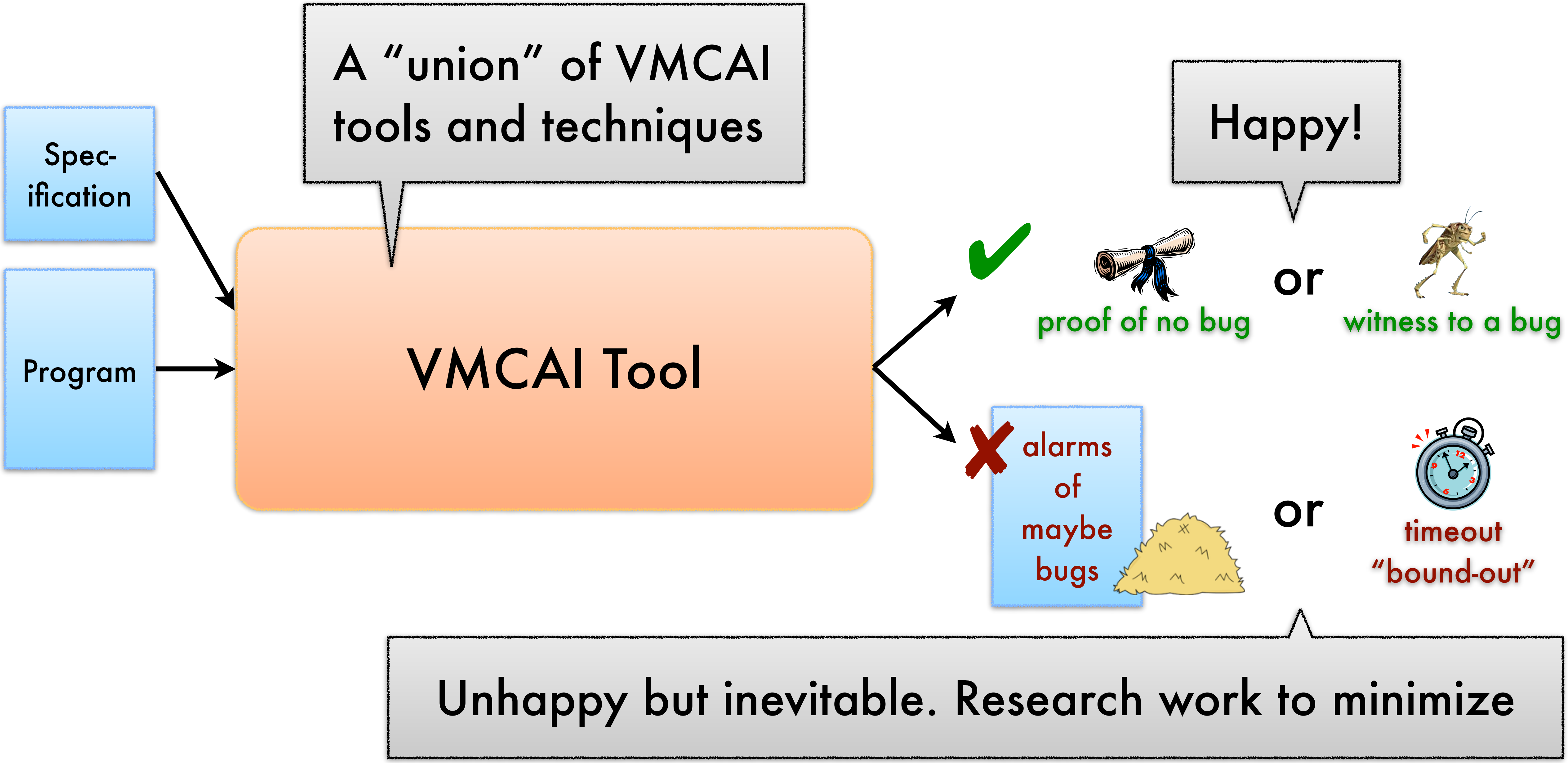
Perspective: The false alarm problem and VMCAI



Spec-ification

Program

A "union" of VMCAI tools and techniques

VMCAI Tool

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Unhappy but inevitable. Research work to minimize

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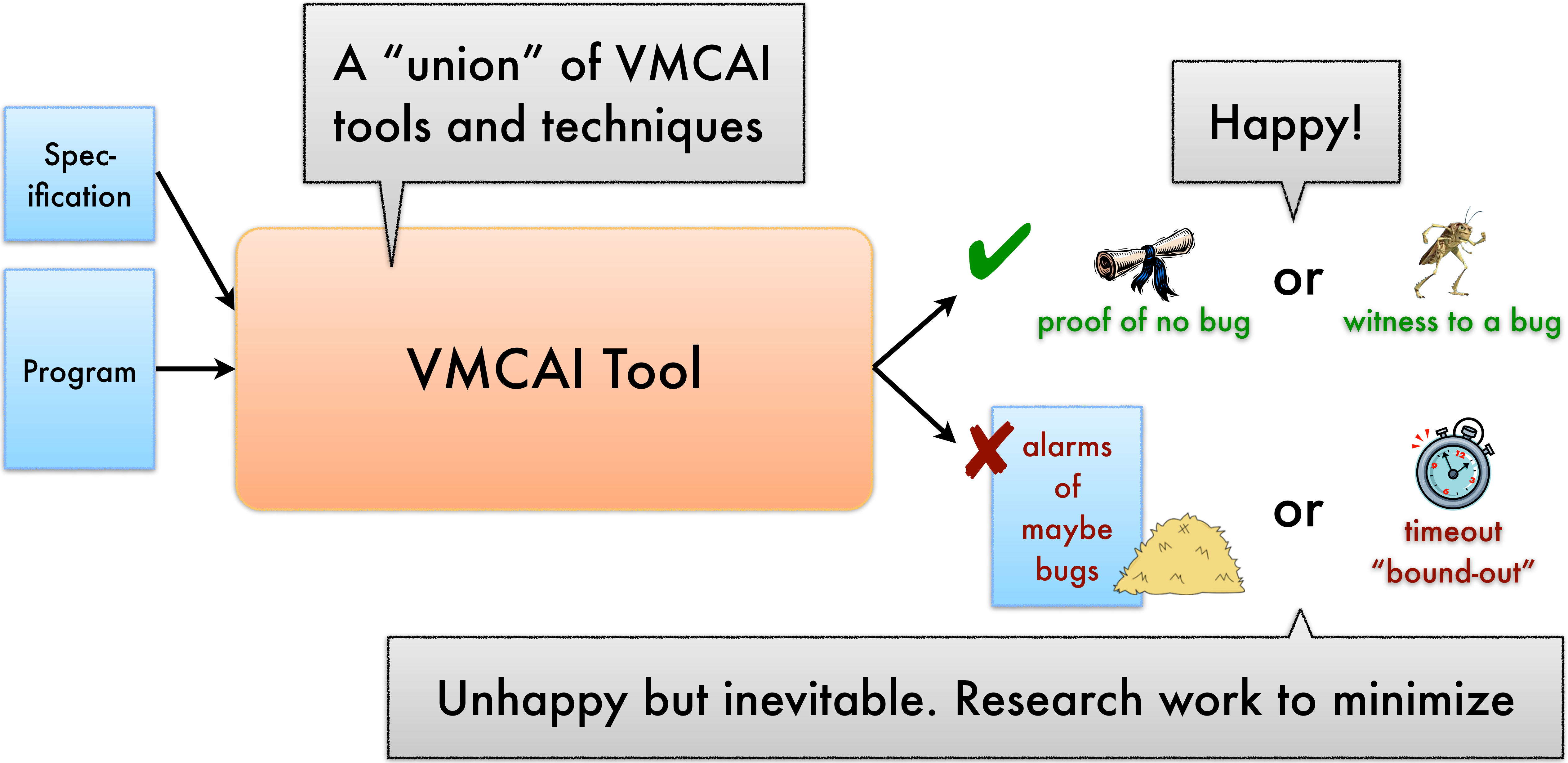

A "union" of VMCAI tools and techniques

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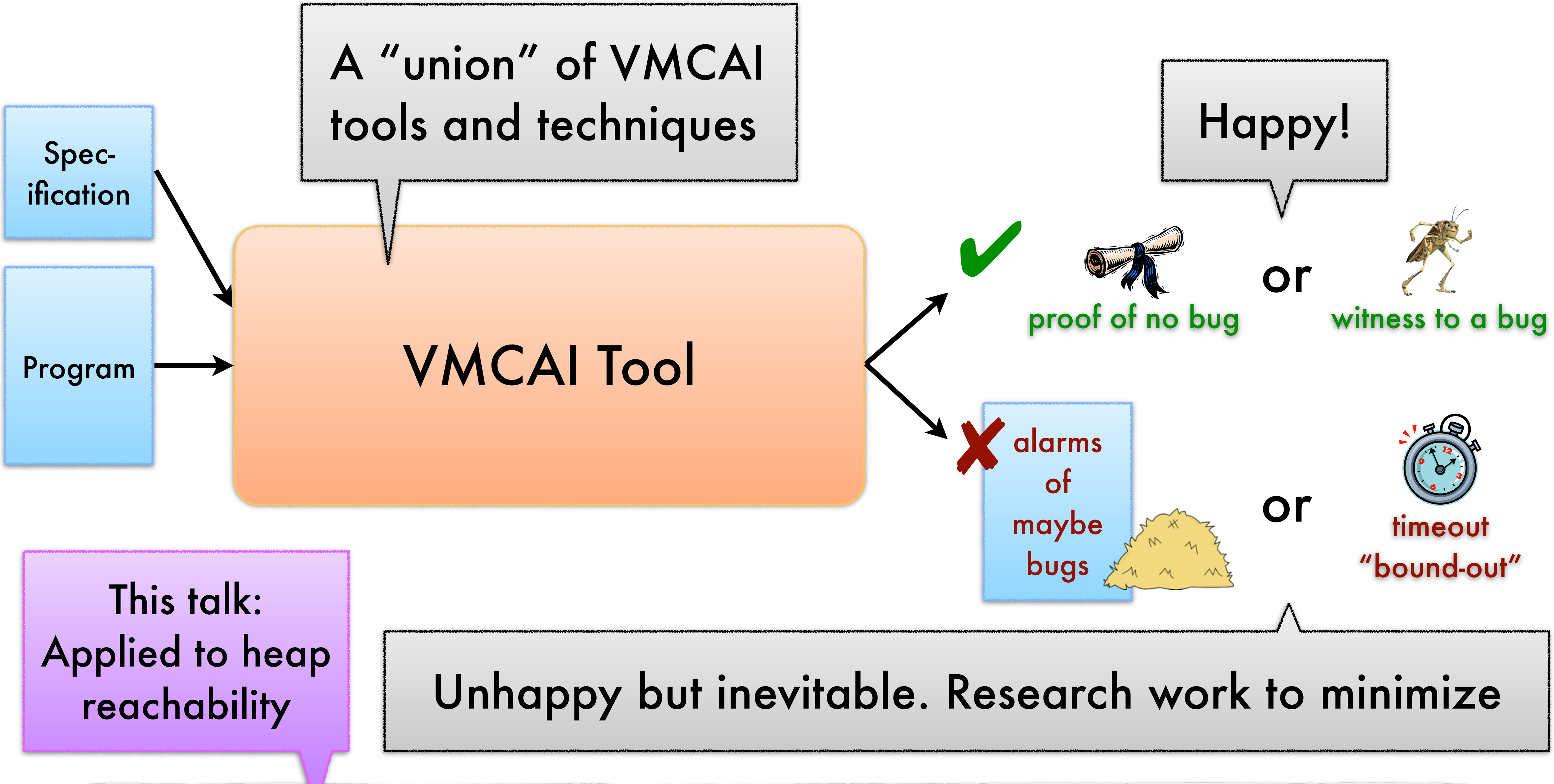
Unhappy but inevitable. Research work to minimize

Spirit of VMCAI: Recognize strength in combining V-MC-AI approaches

Perspective: The false alarm problem and VMCAI


A "union" of VMCAI tools and techniques

Spec-ification

Program

VMCAI Tool

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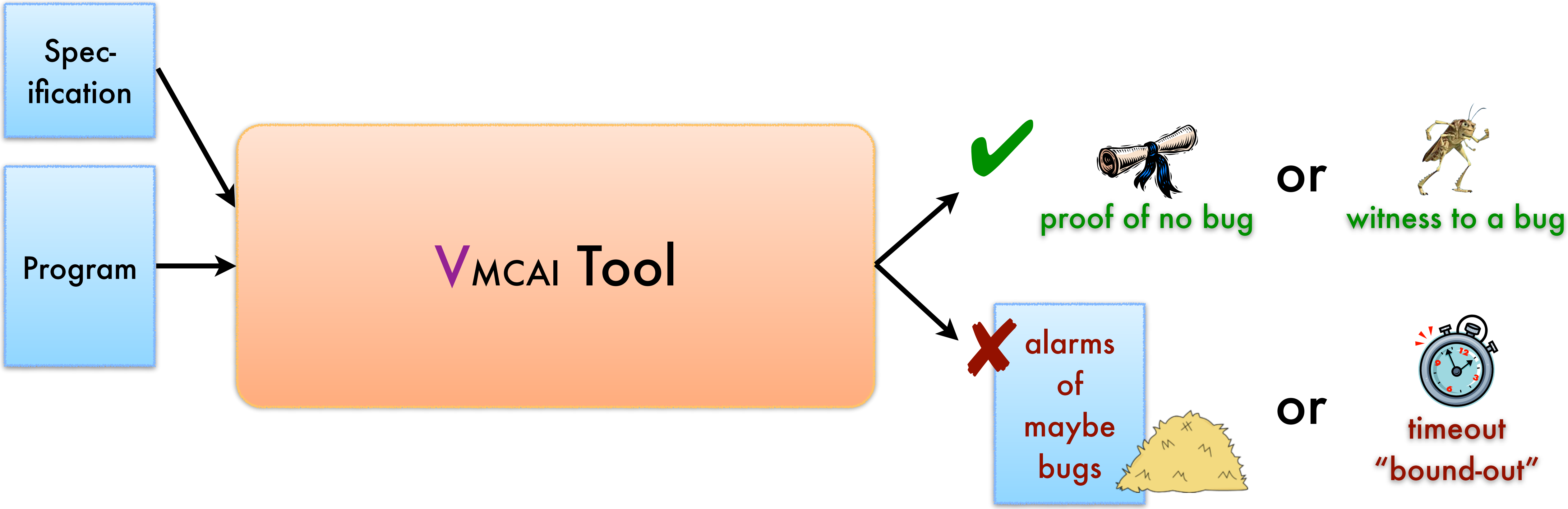
This talk: Applied to heap reachability

Spirit of VMCAI: Recognize strength in combining V-MC-AI approaches

VMCAI: Make tradeoffs based on focus



Spec-ification

Program

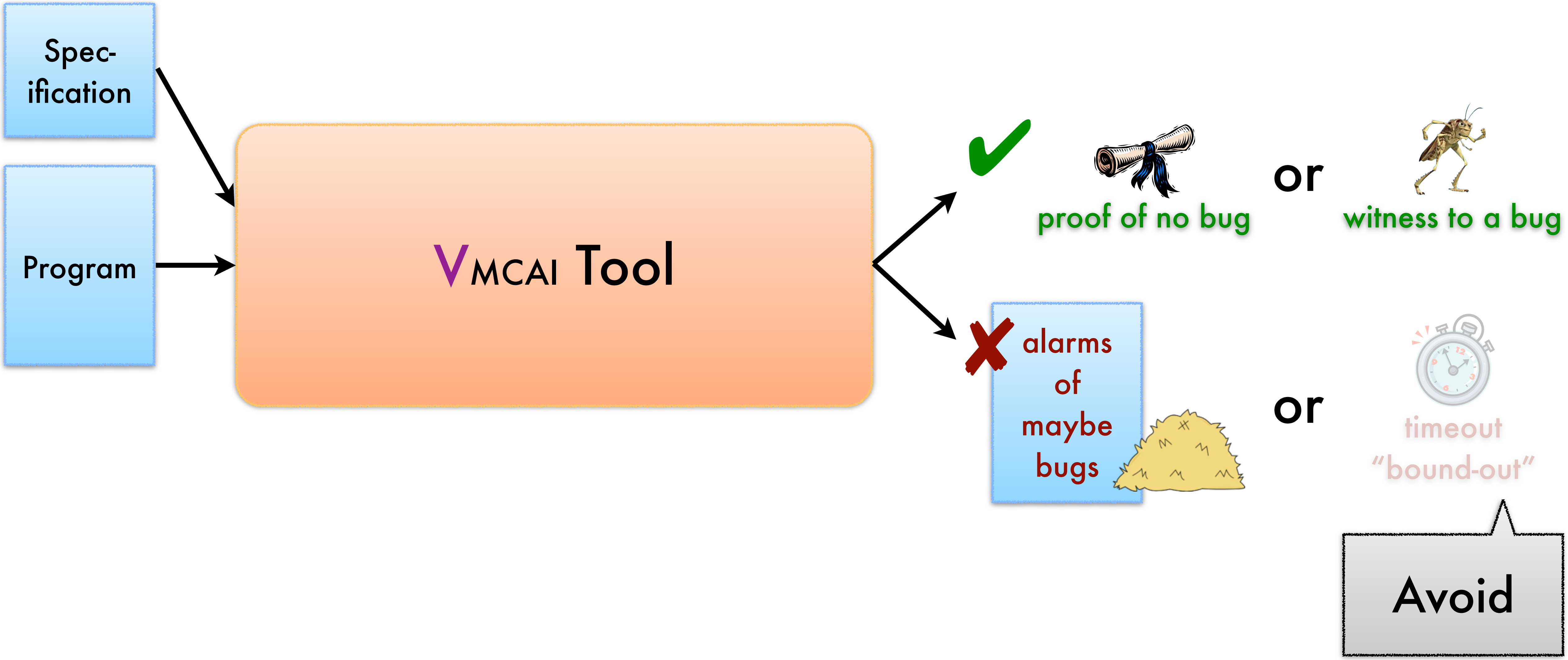
VMCAI Tool

✔ proof of no bug or witness to a bug

✘ alarms of maybe bugs or timeout "bound-out"

Dijkstra, Floyd, Hoare, …
ESC, Spec#, Boogie, Caduceus, Havoc, Calysto, Jahob, VCC, Dryad, …

VMCAI: Make tradeoffs based on focus



Spec-
ification

Program

VMCAI Tool

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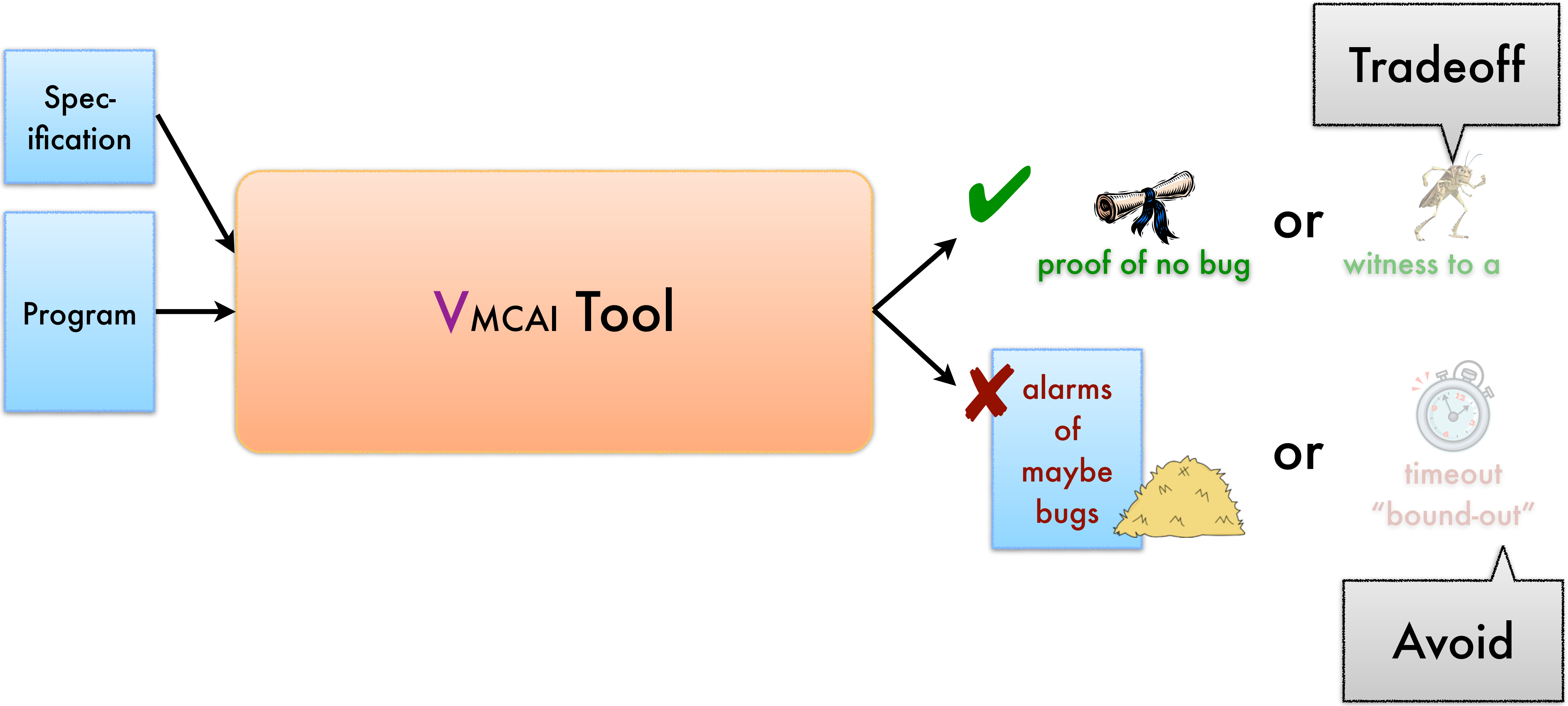

Spec-ification

Program

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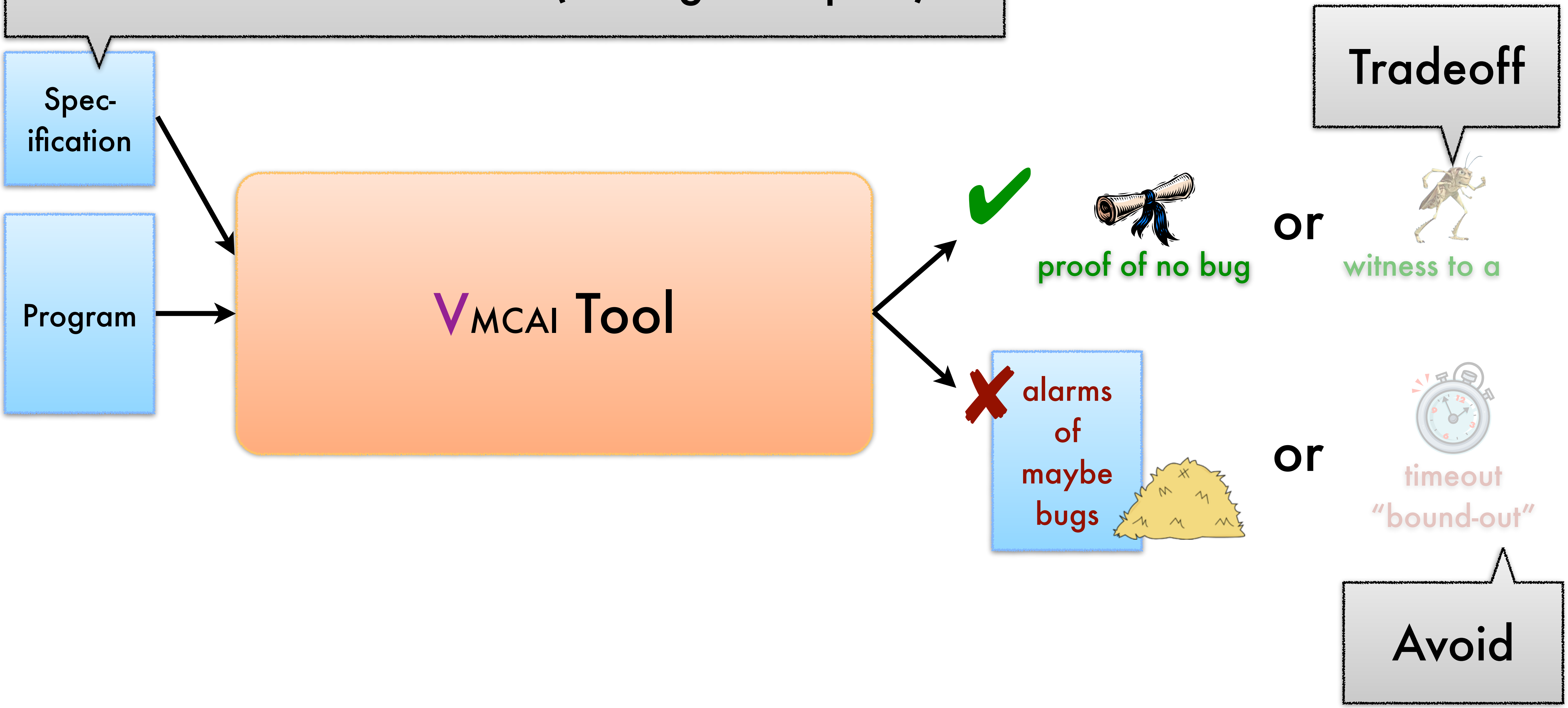
VMCAI: Make tradeoffs based on focus

Expressivity and Usability: Specification can eliminate false alarms (the right loopinv)



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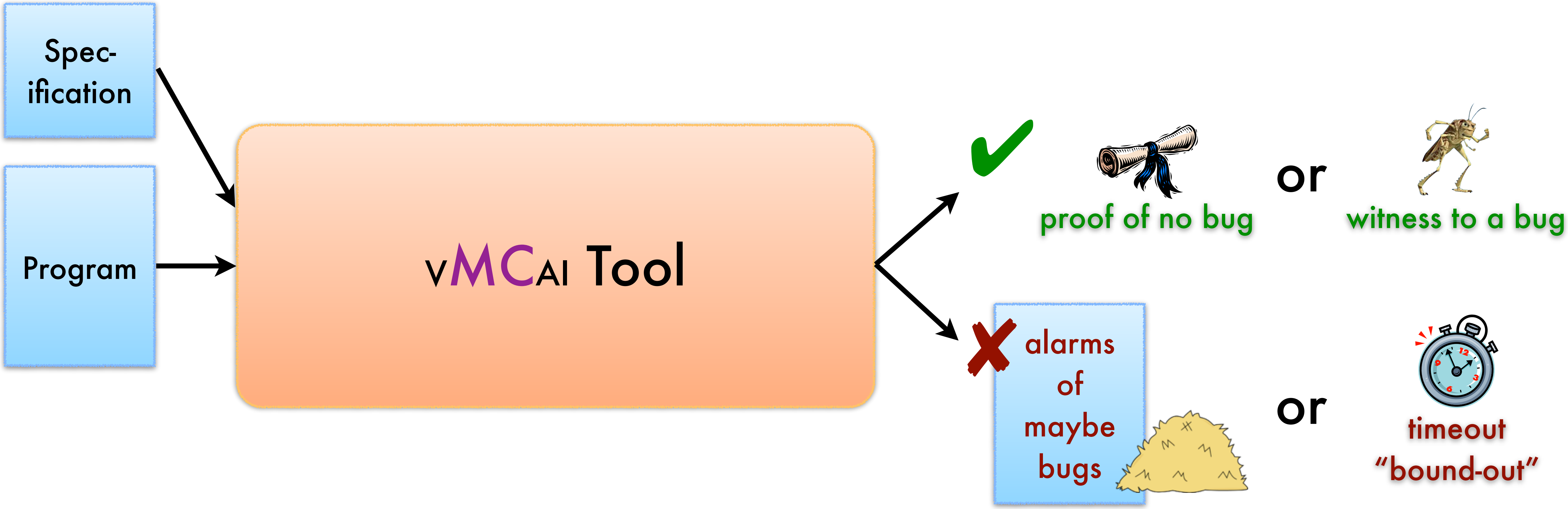
VMCAI: Make tradeoffs based on focus



Specification

Program

VMCAI Tool

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✘ alarms of maybe bugs or timeout "bound-out"

Clarke, Emerson, Sifakis, McMillan, ...
BDDs (SMV, ...), CEGAR (SLAM, Blast, ...), Interpolation (Impact, ...),
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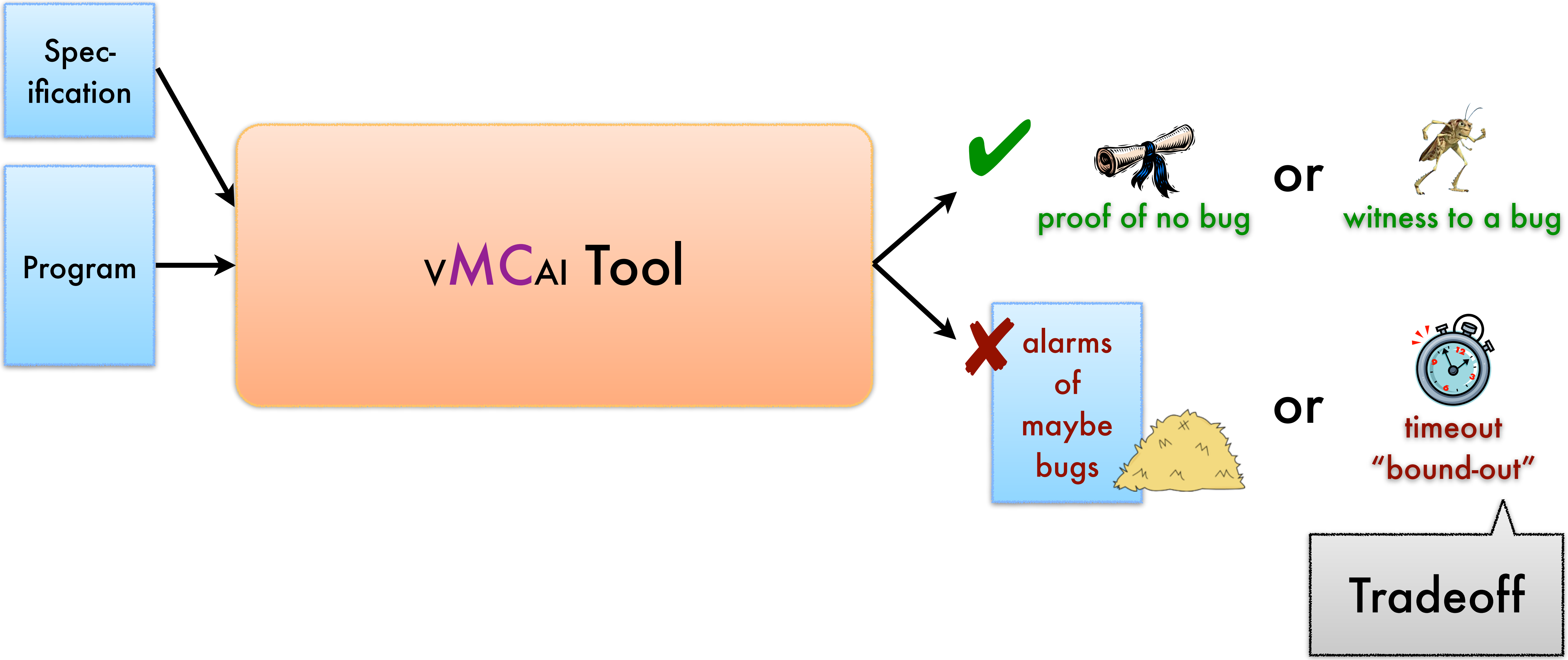
VMCAI: Make tradeoffs based on focus



Spec-ification

Program

vMCAI Tool

✔ proof of no bug

or

witness to a bug

✘ alarms of maybe bugs

or

timeout
"bound-out"

Tradeoff

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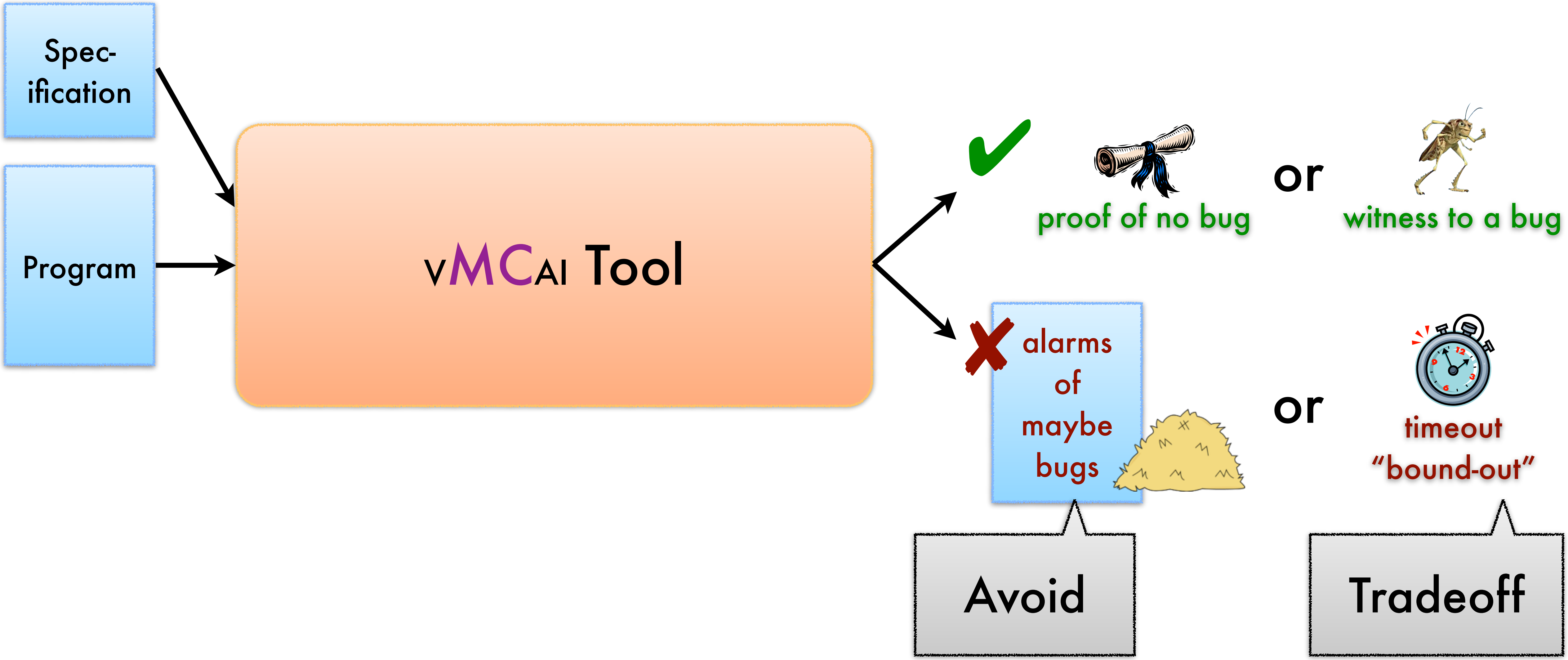
VMCAI: Make tradeoffs based on focus



Spec-ification

Program

vMCAI Tool

✔ proof of no bug

or

witness to a bug

✗ alarms of maybe bugs

or

timeout "bound-out"

Avoid

Tradeoff

Clarke, Emerson, Sifakis, McMillan, …
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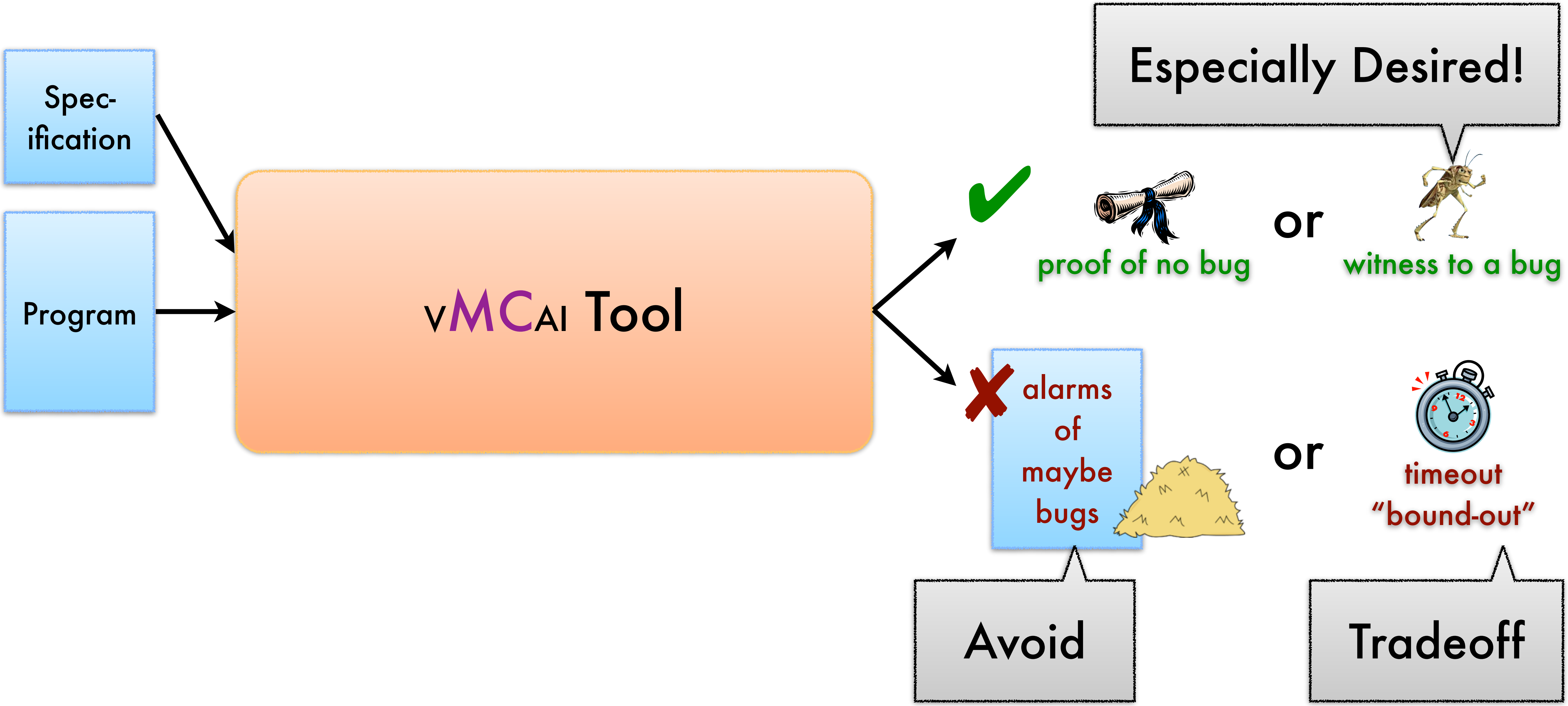
VMCAI: Make tradeoffs based on focus



Spec-ification

Program

VMCAI Tool

✔ proof of no bug or witness to a bug

Especially Desired!

✘ alarms of maybe bugs or timeout "bound-out"

Avoid

Tradeoff

Clarke, Emerson, Sifakis, McMillan, ...
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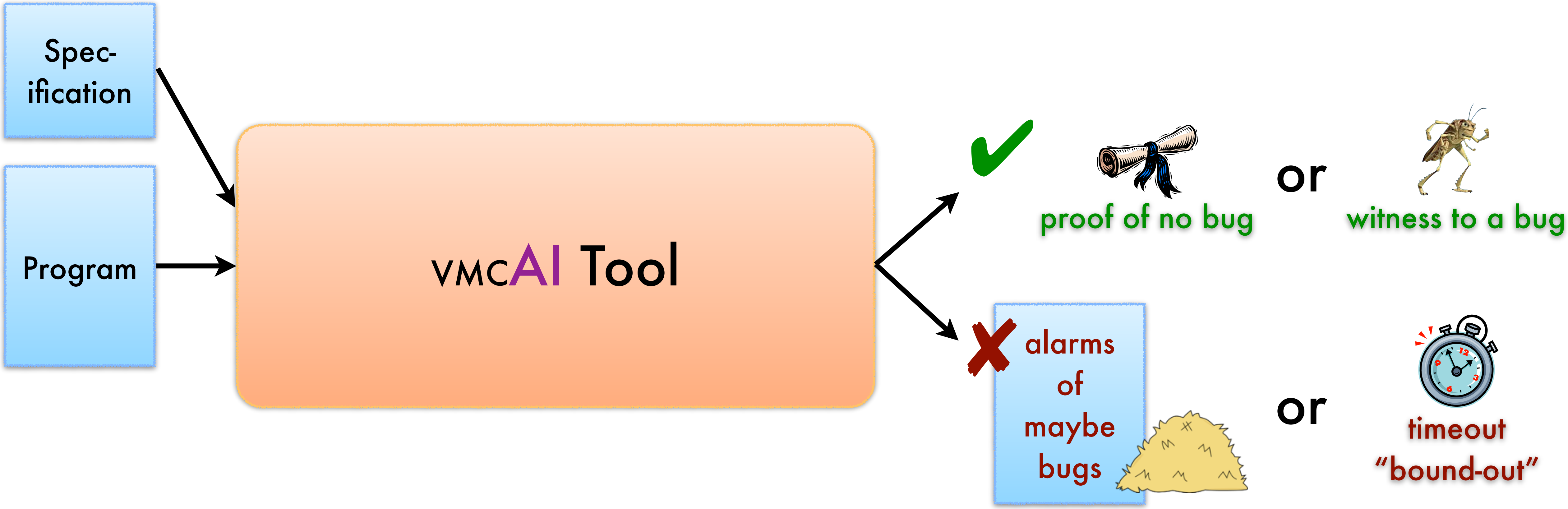
VMCAI: Make tradeoffs based on focus



Spec-ification

Program

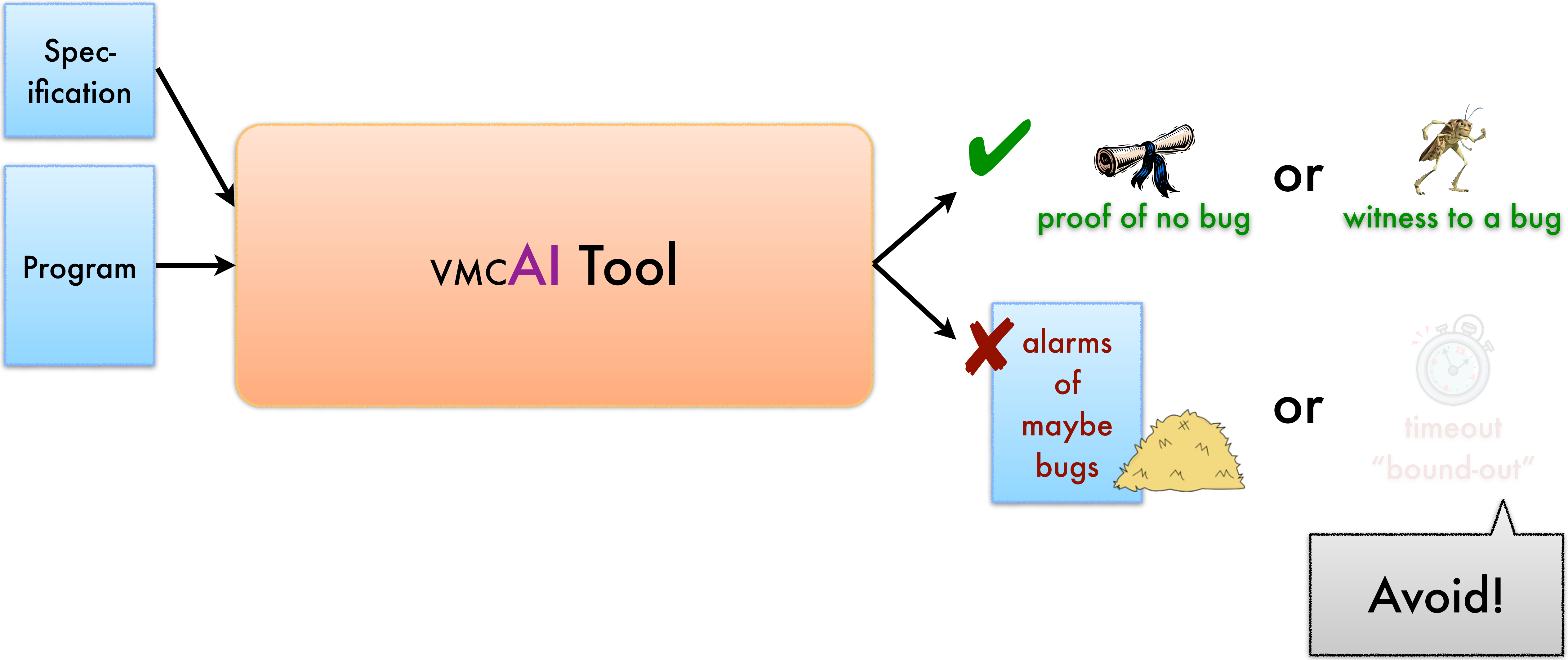
VMCAI Tool

✔ proof of no bug or witness to a bug

✘ alarms of maybe bugs or timeout "bound-out"

Cousot, Cousot, ...
Polyhedra/Octagons/... (Apron), Astrée, Polyspace, Fluctuat, Clousot, SpaceInvader, Slayer, ...

VMCAI: Make tradeoffs based on focus



Spec-ification

Program

vmcAI Tool

✔ proof of no bug or witness to a bug

✘ alarms of maybe bugs or timeout "bound-out"

Avoid!

Cousot, Cousot, ...
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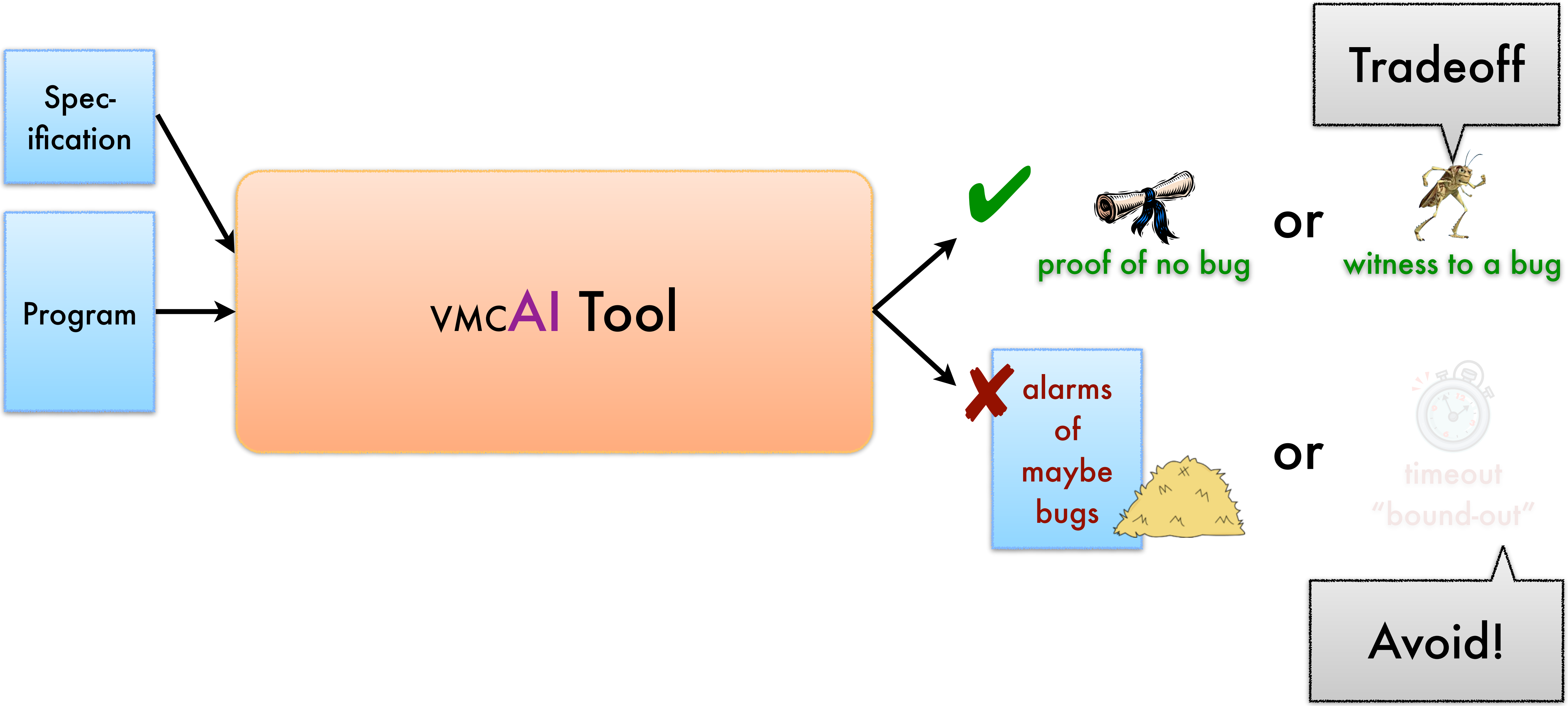
VMCAI: Make tradeoffs based on focus



Spec-ification

Program

VMCAI Tool

✔ proof of no bug

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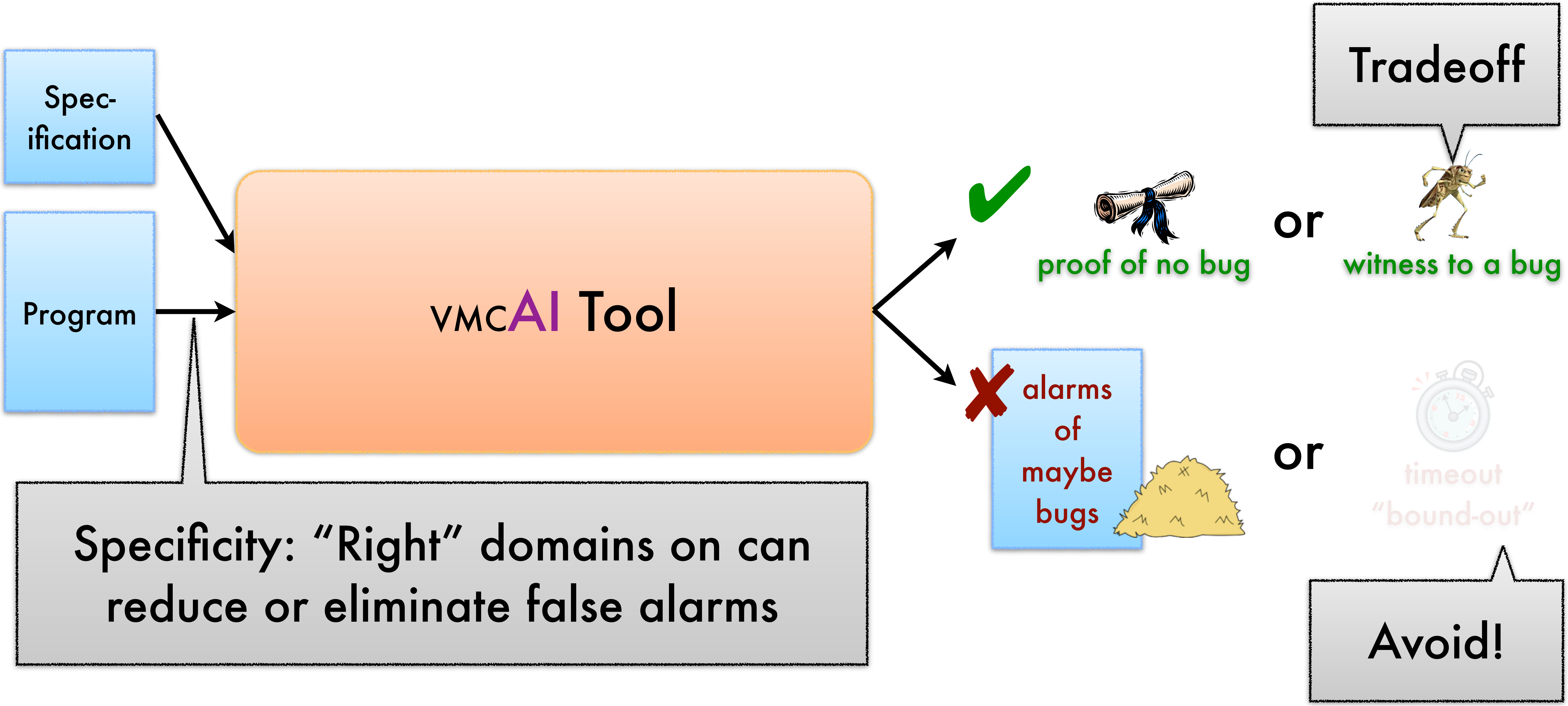


Spec-ification

Program

VMCAI Tool

✓ proof of no bug

or

witness to a bug

Tradeoff

✗ alarms of maybe bugs

or

timeout "bound-out"

Avoid!

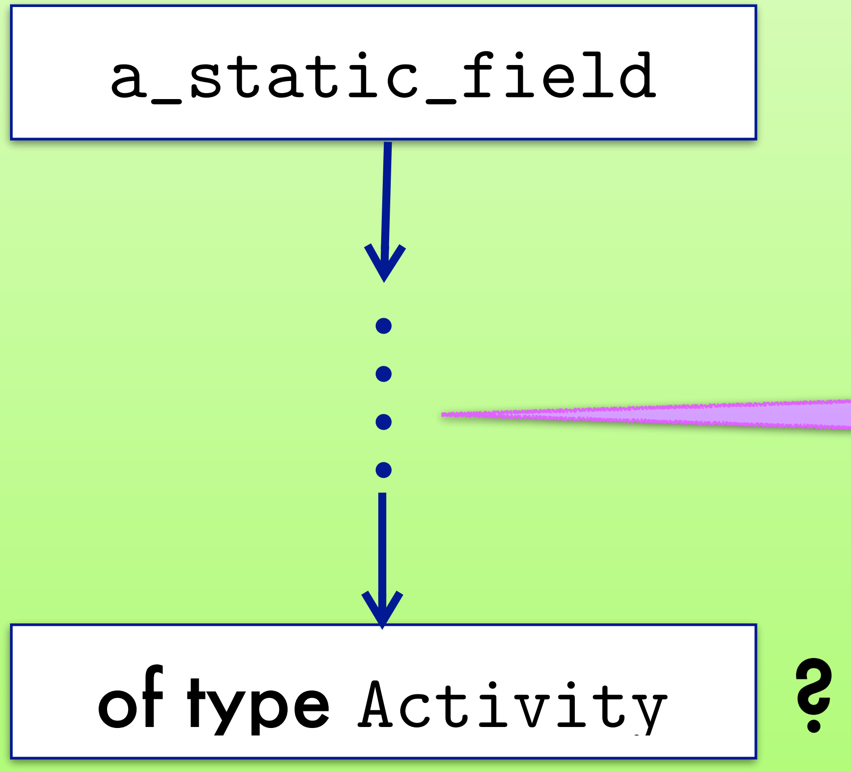
Specificity: "Right" domains on can reduce or eliminate false alarms

Cousot, Cousot, ...
Polyhedra/Octagons/... (Apron), Astrée, Polyspace, Fluctuat, Clousot, SpaceInvader, Slayer, ...

Back to …

A candidate for statically answering, “Is there an `Activity` leak?”

Is there a program execution where at some time



`a_static_field`

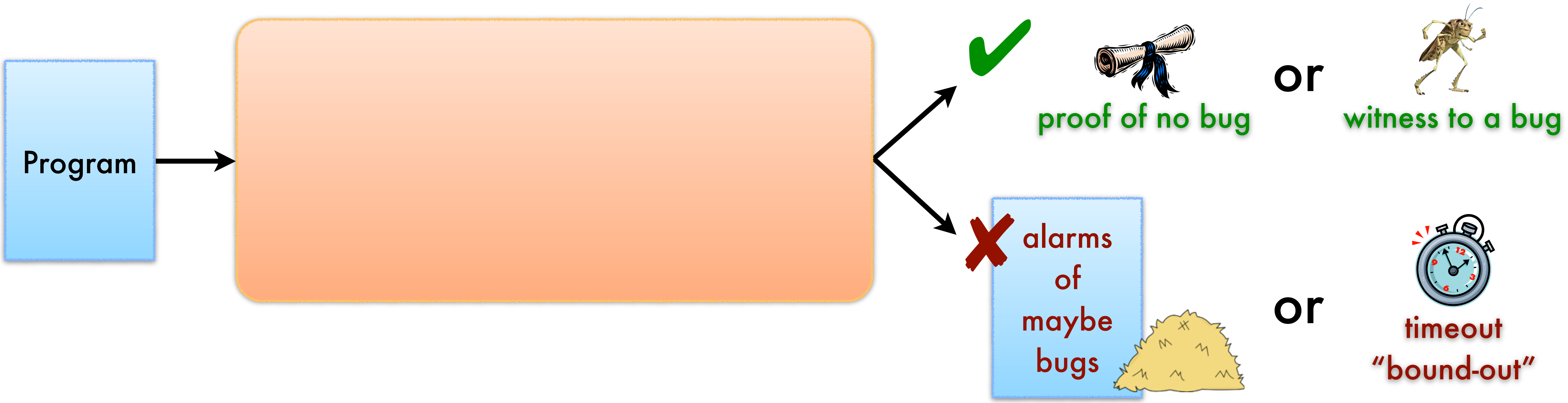
`of type Activity` ?

Can be answered with a points-to analysis

Compute a points-to graph and look for such points-to paths

This won’t work because …

Thresher [SAS'11,PLDI'13] attacks alarm triage for heap reachability properties



Program

✔ proof of no bug or witness to a bug

✘ alarms of maybe bugs or timeout "bound-out"

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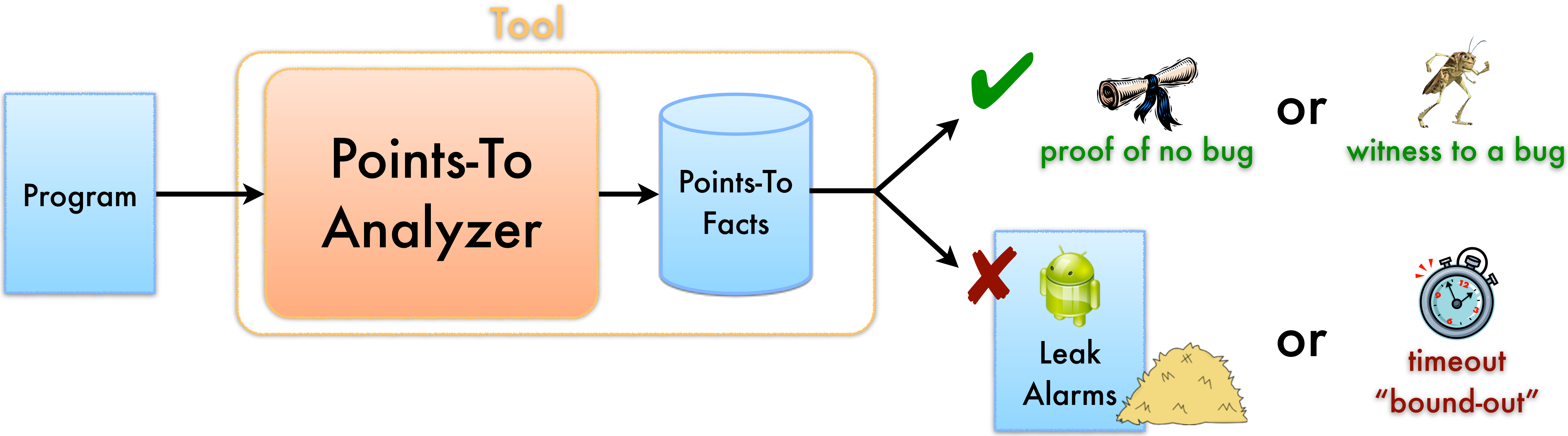

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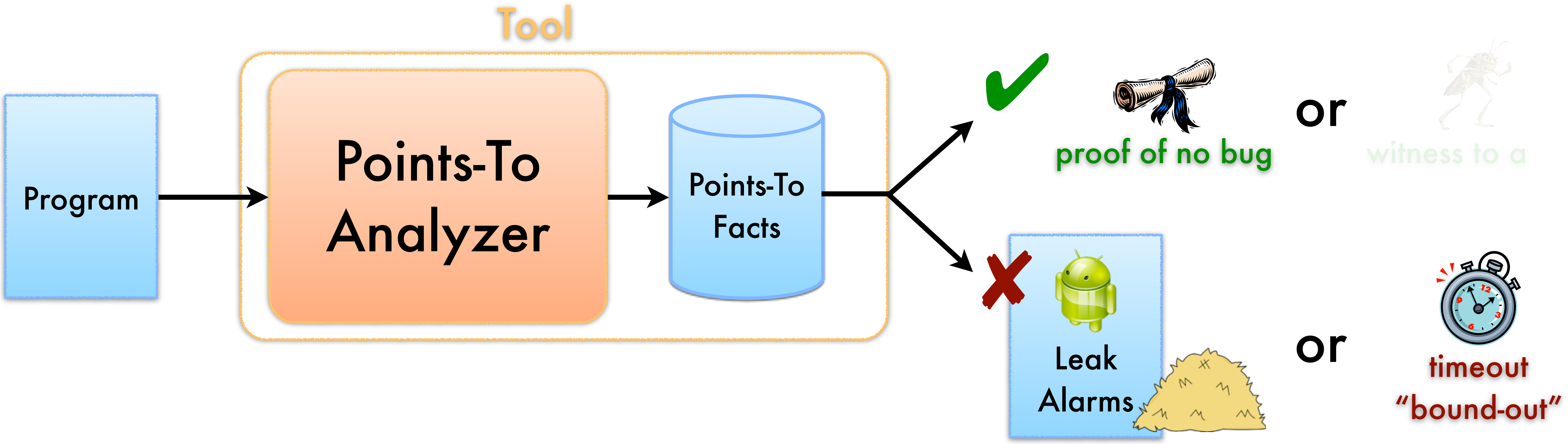

Tool

Program

Points-To Analyzer

Points-To Facts

✔ proof of no bug

or

witness to a

✘ Leak Alarms

or

timeout "bound-out"

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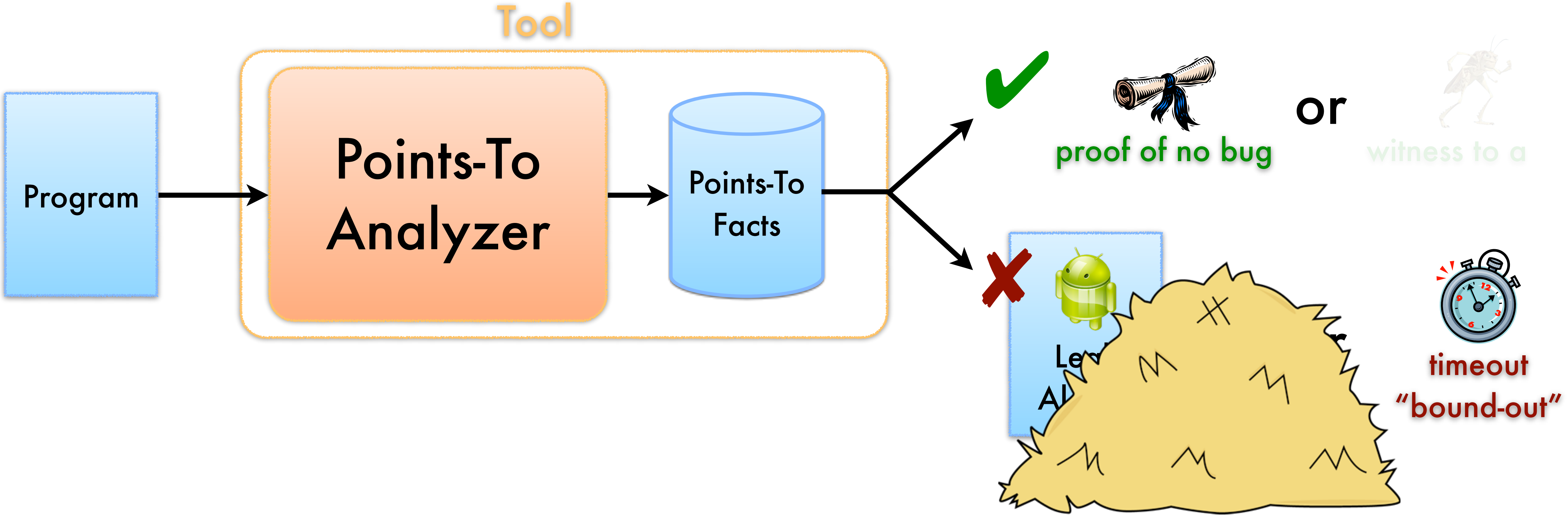

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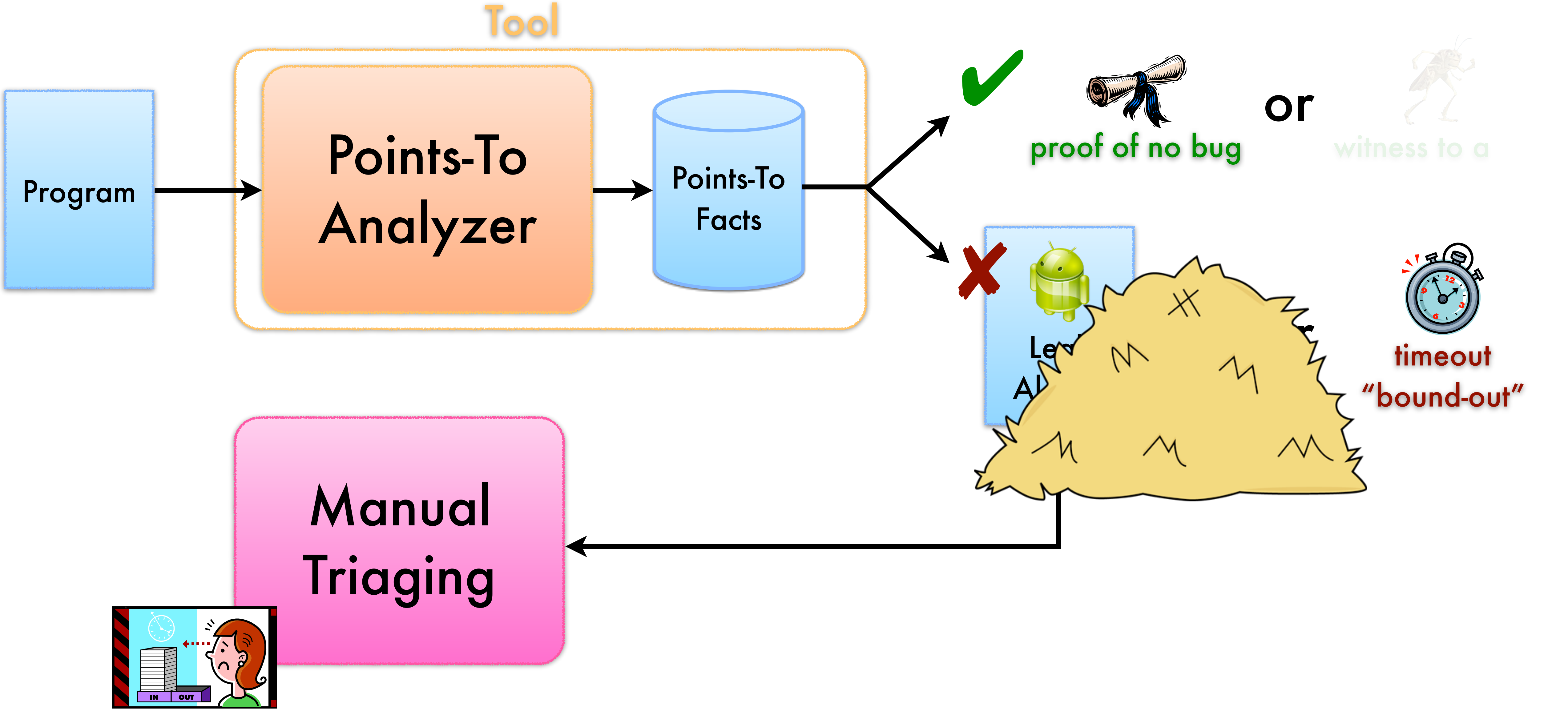

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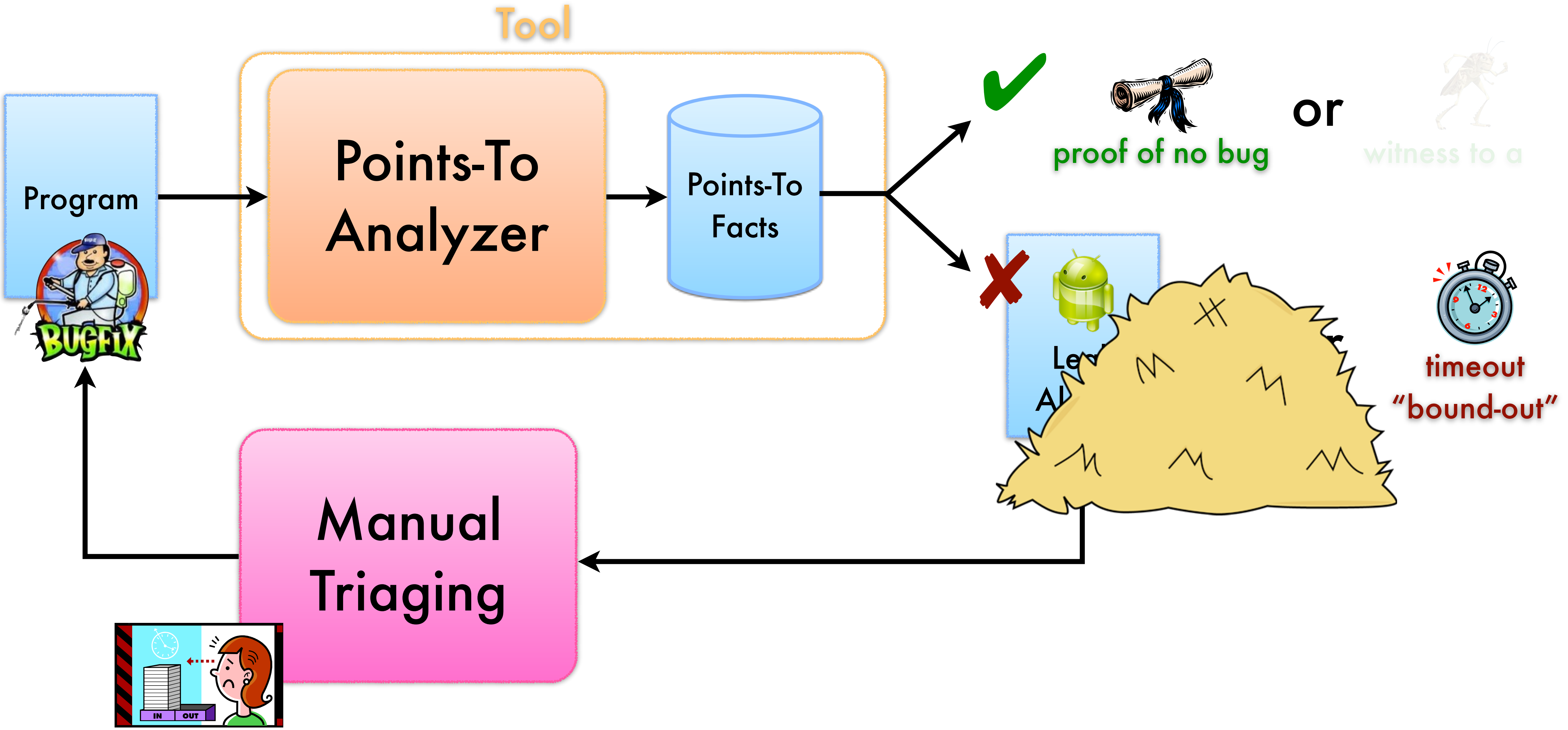

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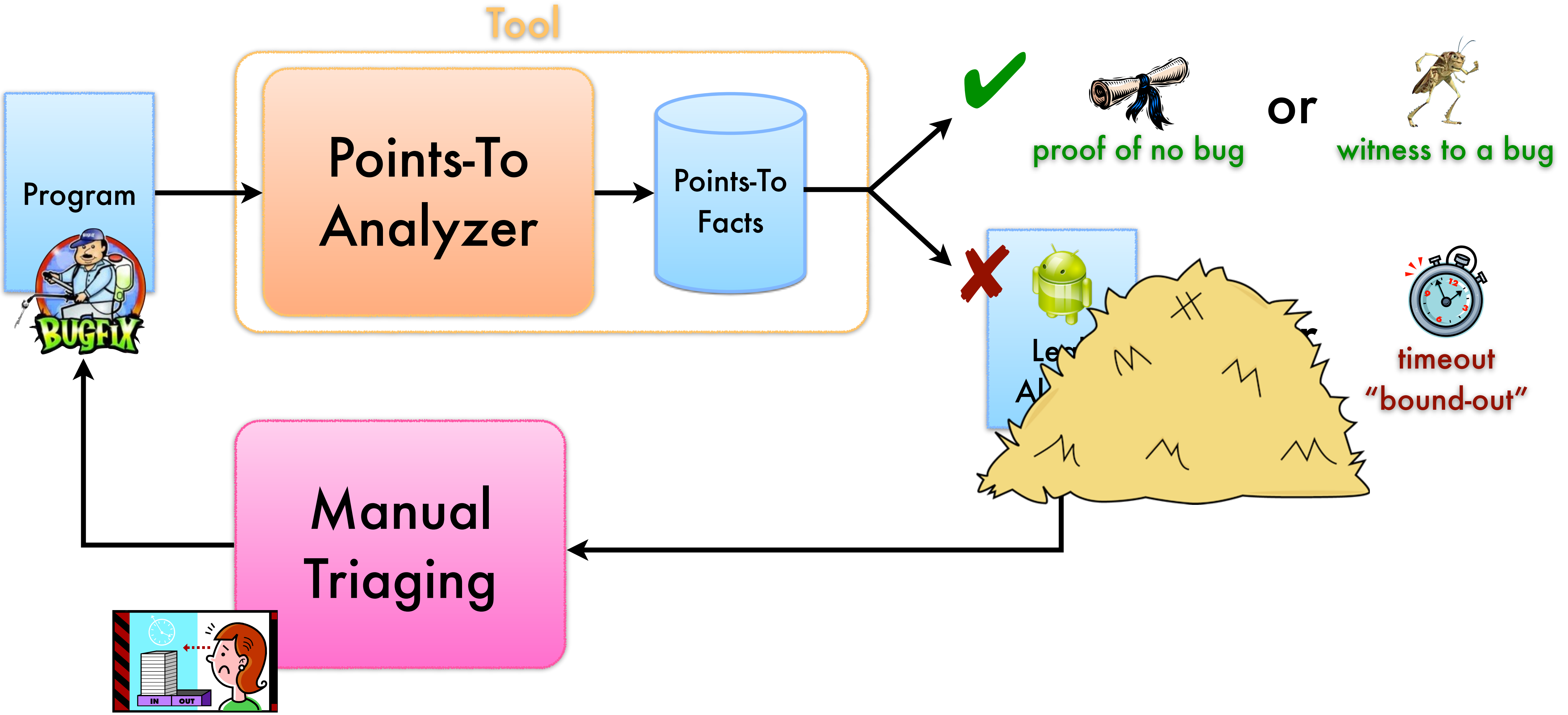

Tool

Program

Points-To Analyzer

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"bound-out"

Manual Triaging

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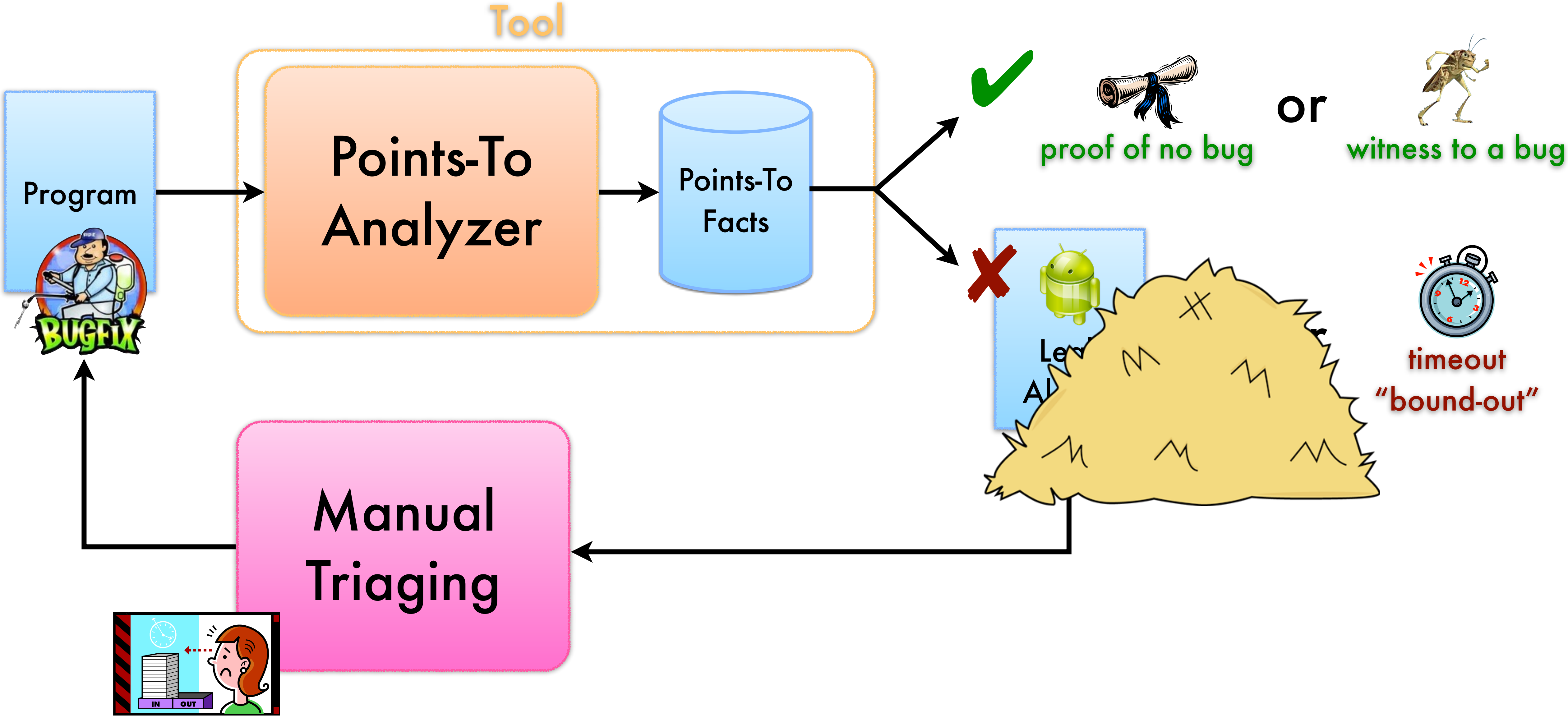
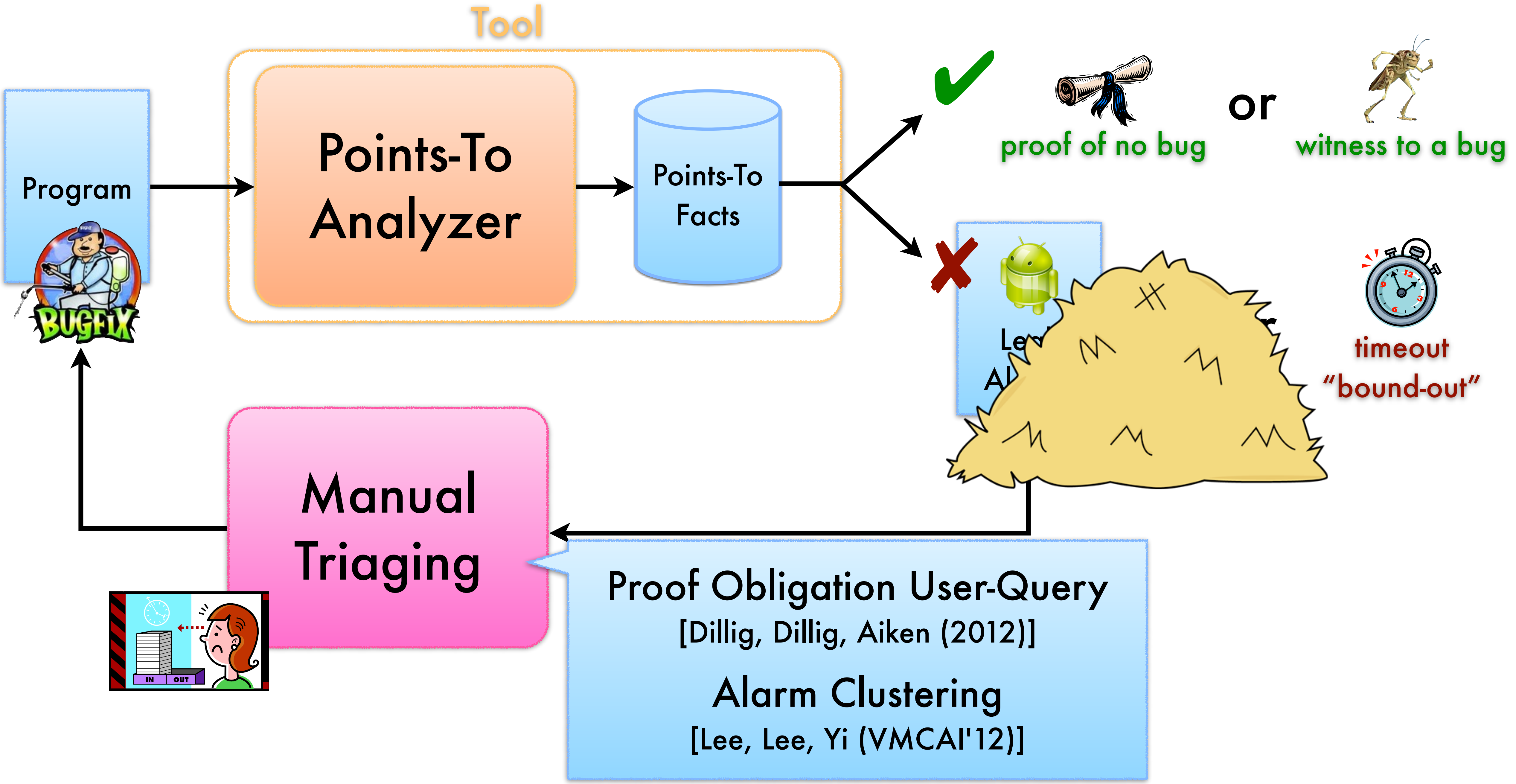


Prove alarms false with a witness search

Thresher [SAS'11,PLDI'13] attacks alarm **triage** for heap reachability properties



Tool

Program

Points-To Analyzer

Points-To Facts

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✘ Le Al

timeout "bound-out"

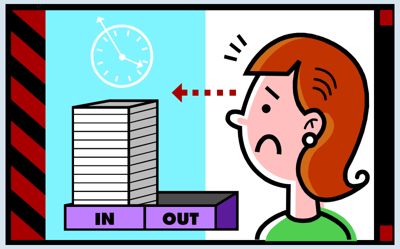
Manual Triaging

Proof Obligation User-Query [Dillig, Dillig, Aiken (2012)]

Alarm Clustering [Lee, Lee, Yi (VMCAI'12)]

Prove alarms false with a witness search

Manual triage for heap reachability reports



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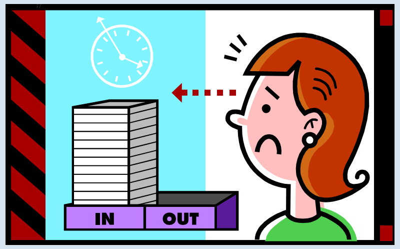

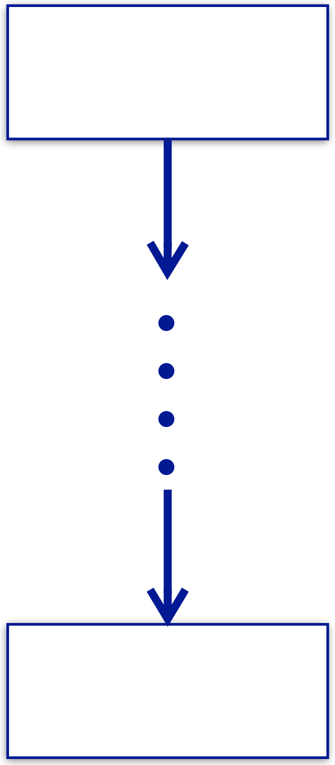

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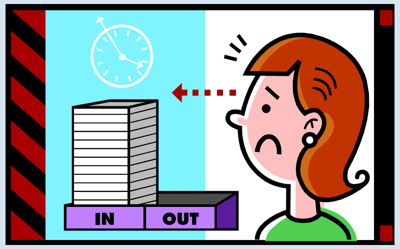
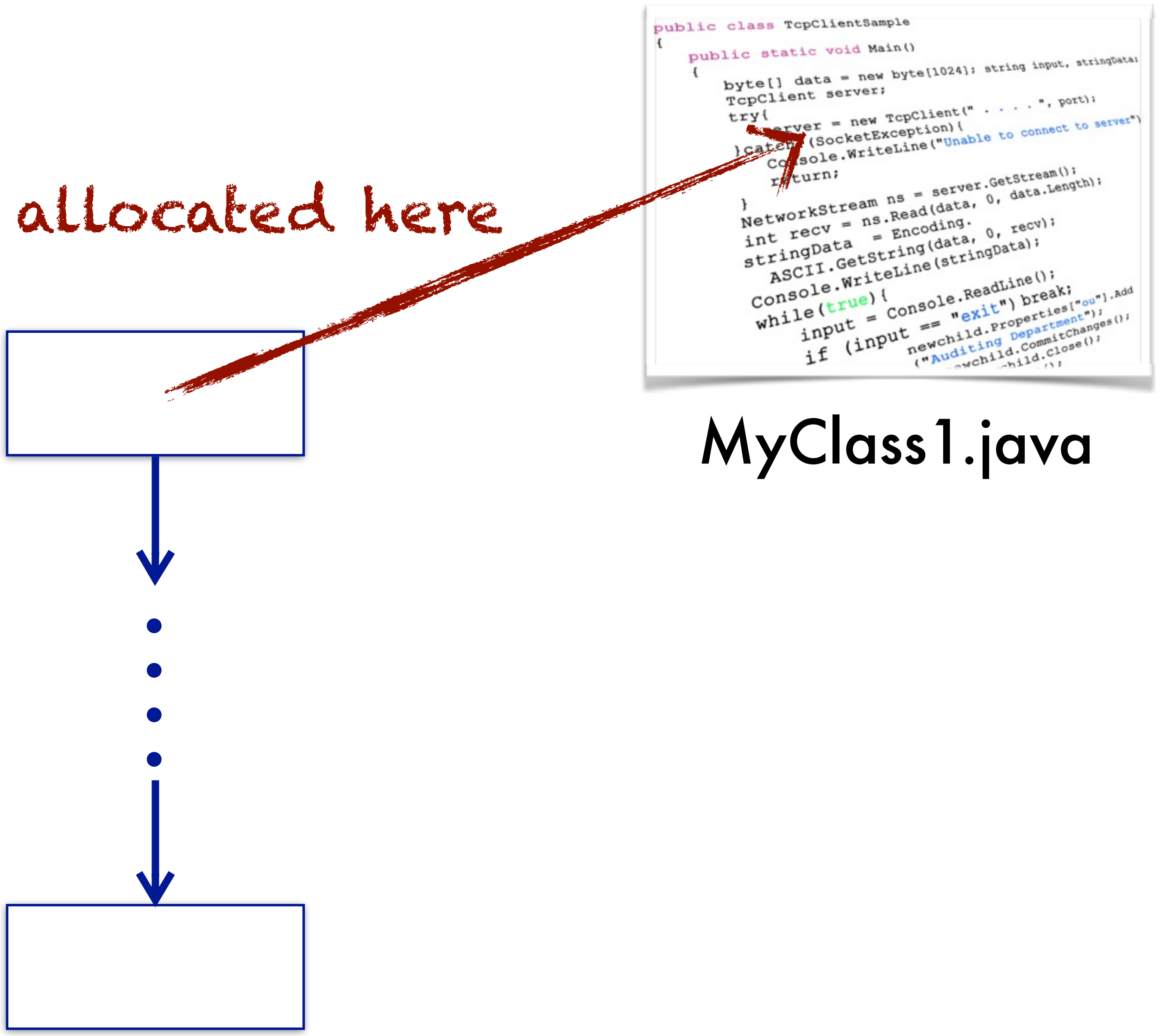


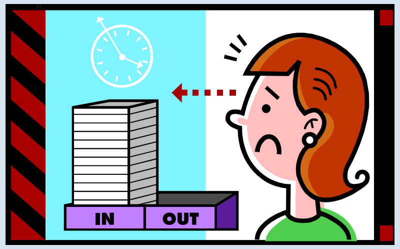


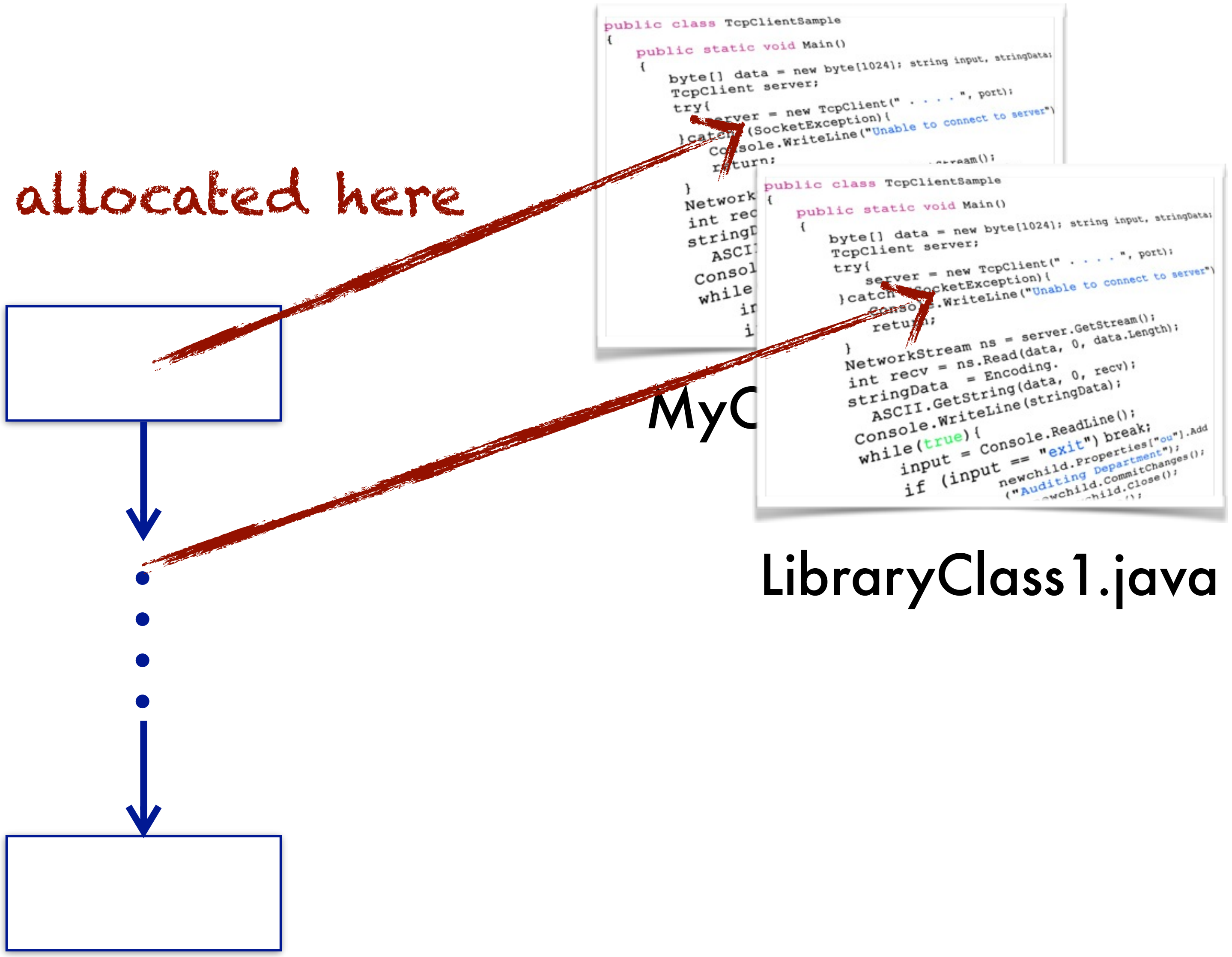
allocated here

```
public class TcpClientSample
{
    public static void Main()
    {
        byte[] data = new byte[1024]; string input, stringData;
        TcpClient server;
        try{
            server = new TcpClient(" . . . . ", port);
        }catch (SocketException){
            Console.WriteLine("Unable to connect to server")
            return;
        }
        NetworkStream ns = server.GetStream();
        int recv = ns.Read(data, 0, data.Length);
        stringData   = Encoding.
            ASCII.GetString(data, 0, recv);
        Console.WriteLine(stringData);
        while(true){
            input = Console.ReadLine();
            if (input == "exit") break;
                newchild.Properties["ou"].Add
                ("Auditing Department");
                newchild.CommitChanges();
                newchild.Close();
```

MyClass1.java

Manual triage for heap reachability reports





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        }
        Network
        int rec
        stringD
          ASCI
        Consol
        while
            in
            i
```

MyC

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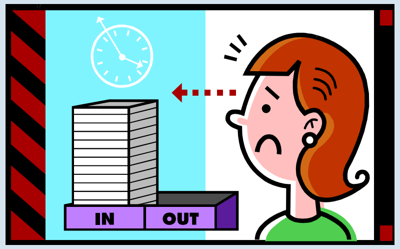
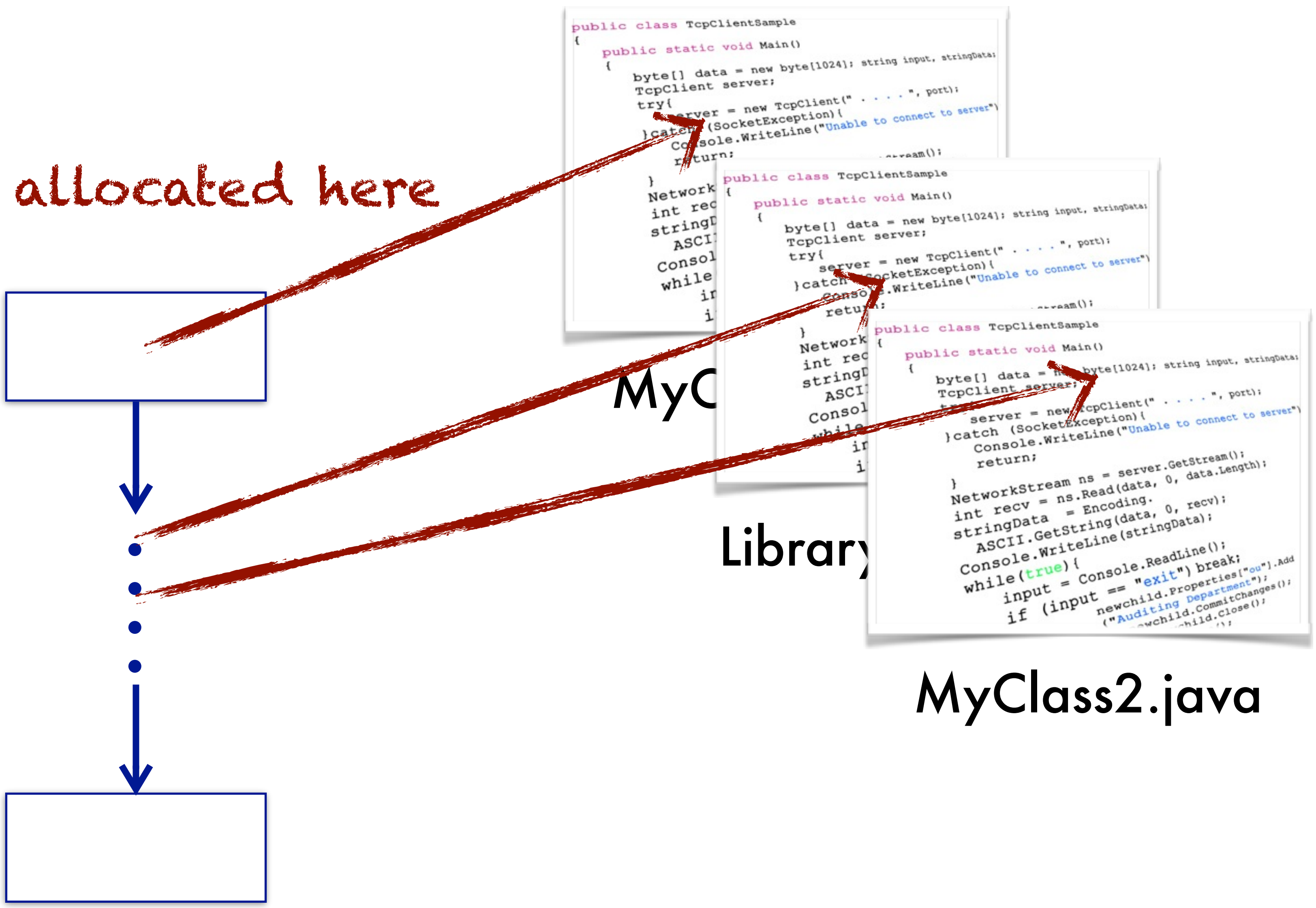
LibraryClass1.java

Manual triage for heap reachability reports





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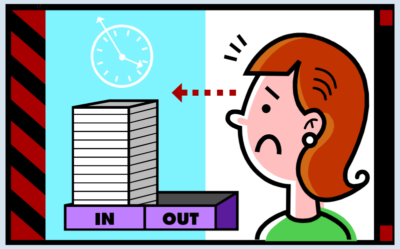
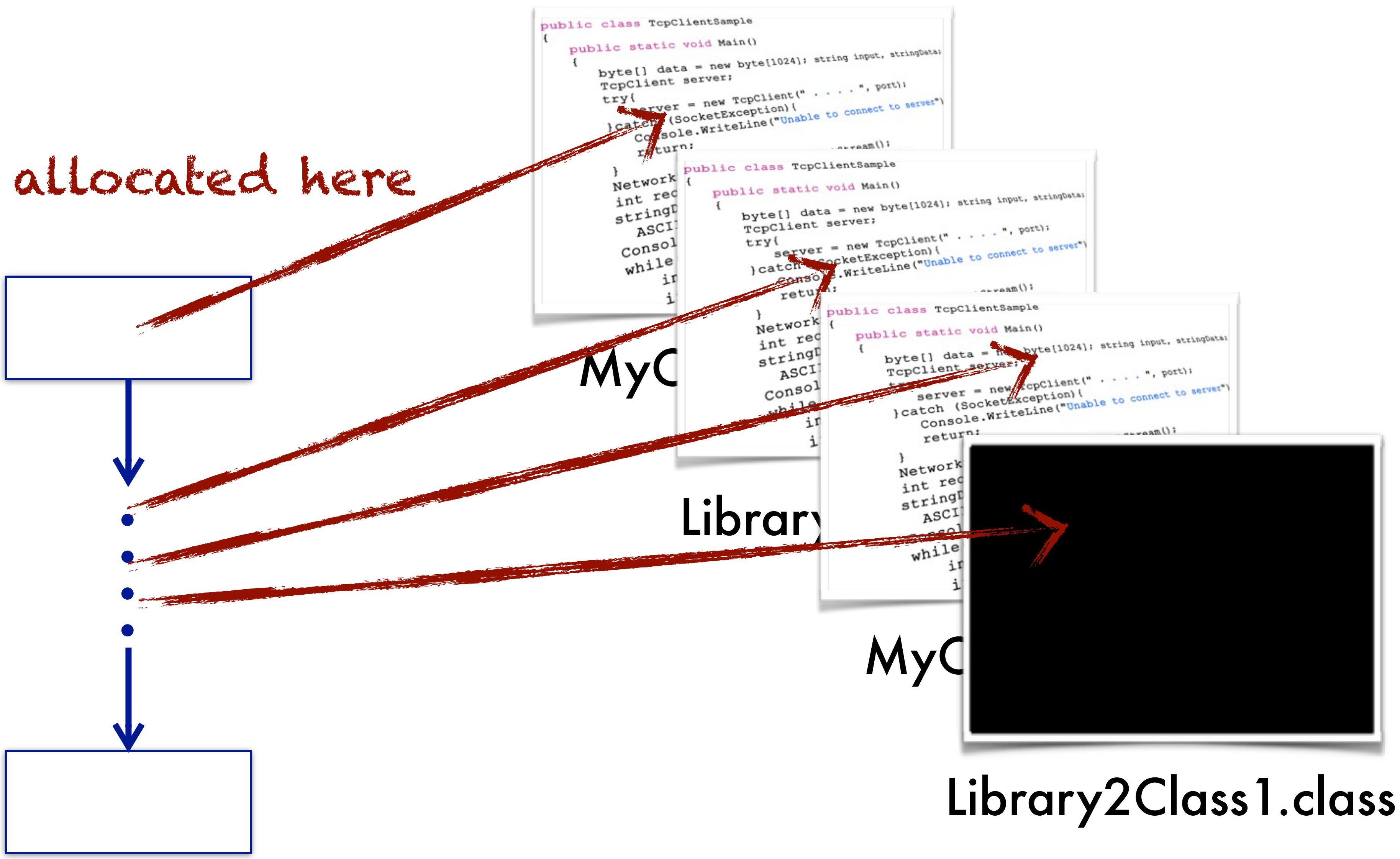
Manual triage for heap reachability reports





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            return;
                                            ...Stream();
        }
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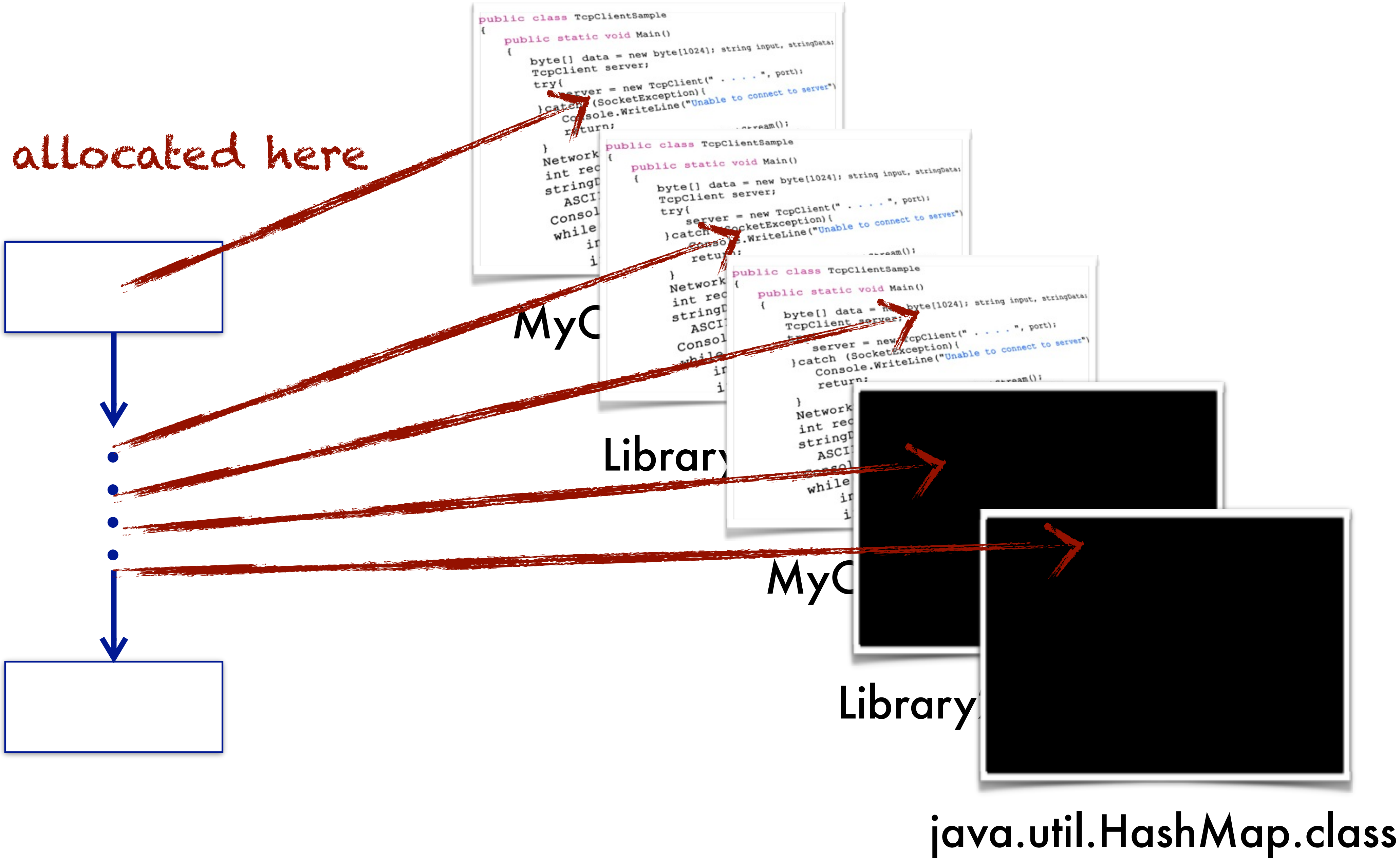
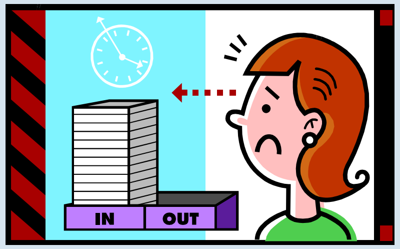
        int rec
        stringD
          ASCI
        Consol
        while
            in
            i
```

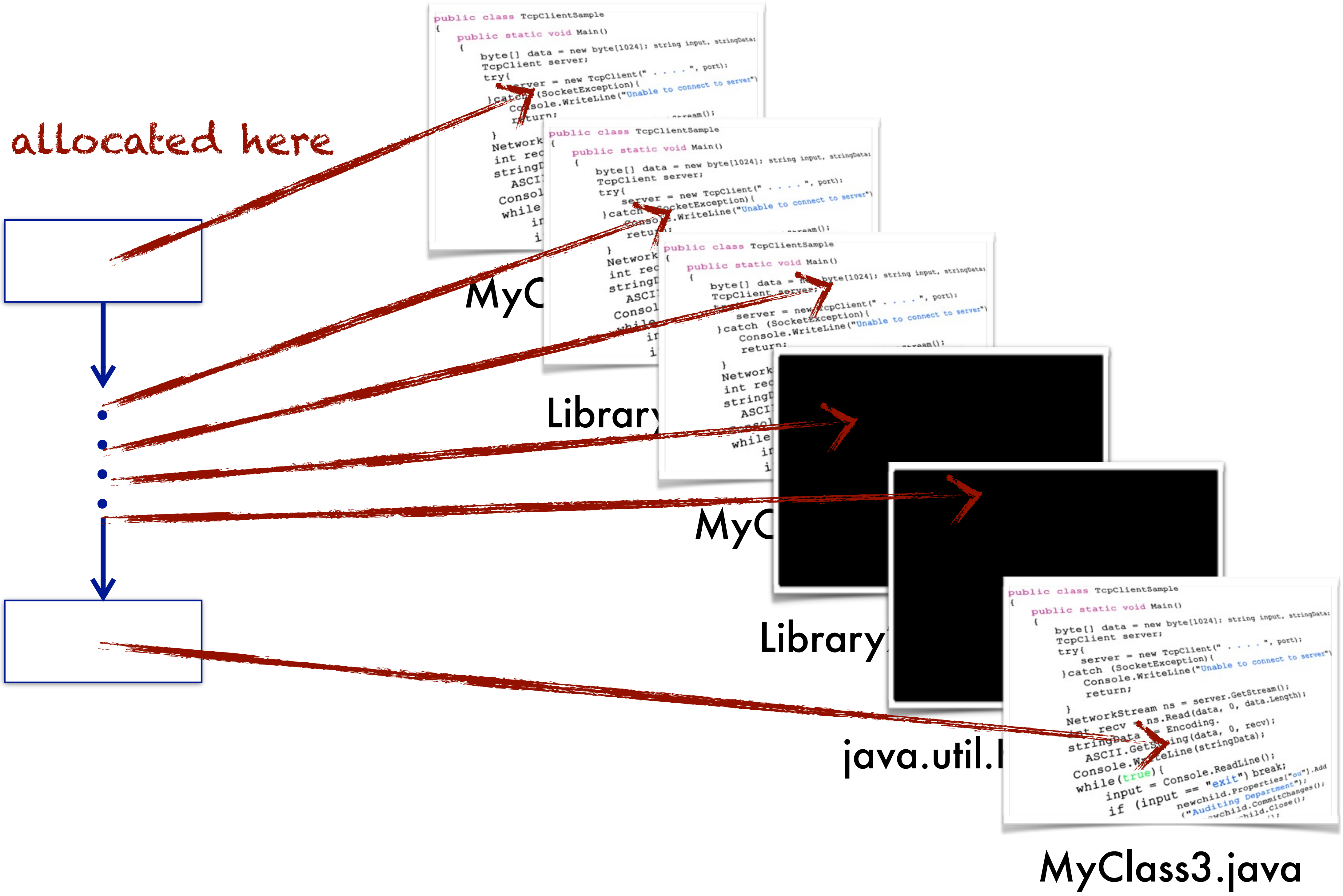
Manual triage for heap reachability reports



```
public class TcpClientSample
{
    public static void Main()
    {
        byte[] data = new byte[1024]; string input, stringData;
        TcpClient server;
        try{
            server = new TcpClient(" . . . . ", port);
        }catch (SocketException){
            Console.WriteLine("Unable to connect to server")
            return;
                                              ...Stream();
        }
        Network
        int rec
        stringD
          ASCI
        Consol
        while
            in
            i
```

Manual triage for heap reachability reports





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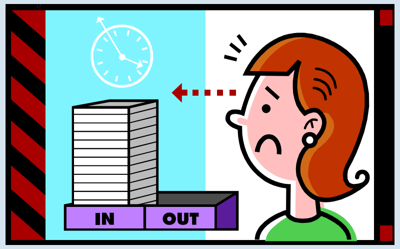
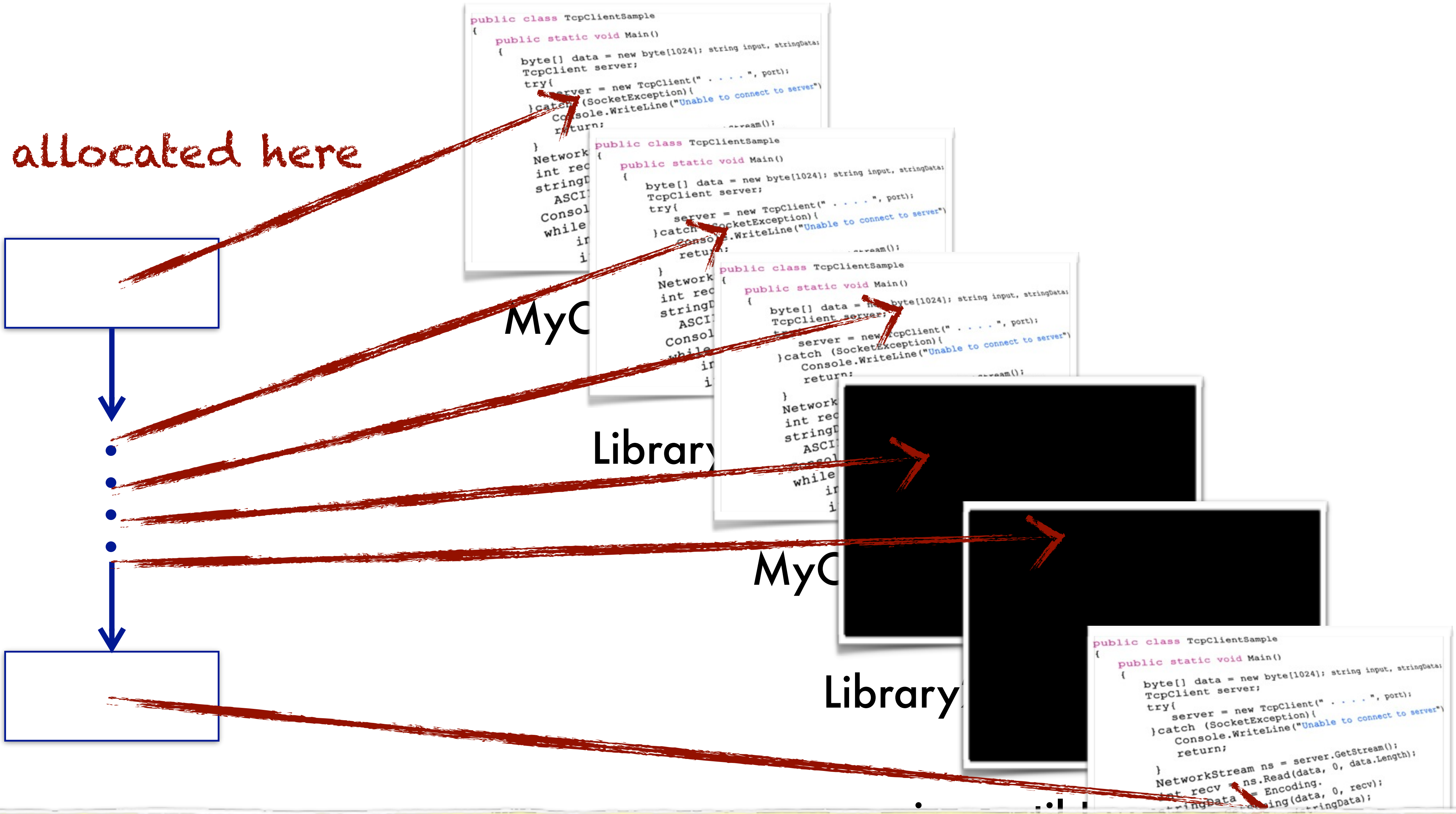
        TcpClient server;
        try{
            server = new TcpClient(" . . . . ", port);
        }catch (SocketException){
            Console.WriteLine("Unable to connect to server")
            return;
        }
        NetworkStream ns = server.GetStream();
        int recv = ns.Read(data, 0, data.Length);
        stringData = Encoding.
          ASCII.GetString(data, 0, recv);
        Console.WriteLine(stringData);
        while(true){
            input = Console.ReadLine();
            if (input == "exit") break;
                newchild.Properties["ou"].Add
                ("Auditing Department");
                newchild.CommitChanges();
                newchild.Close();
```

Manual triage for heap reachability reports





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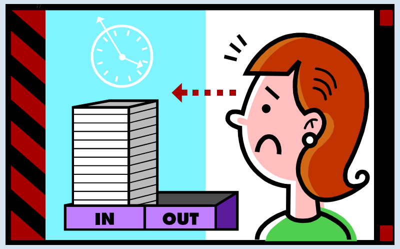
        stringData = Encoding.
            ASCII.GetString(data, 0, recv);
        Console.WriteLine(stringData);
        while
```

Get abstract heap path + allocation sites

Assuming the user starts to triage an alarm ...



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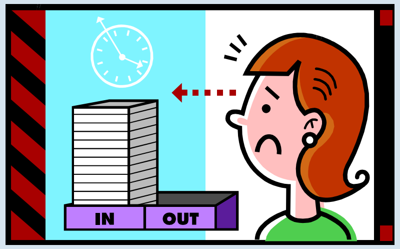
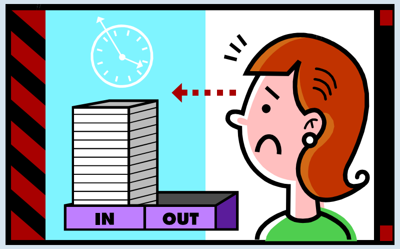


What does the user need to do? He starts at, say, line 142 and traces back to see if a bug is possible given what's happening.

Assuming the user starts to triage an alarm ...



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We can do this with analysis (V+MC+AI)!

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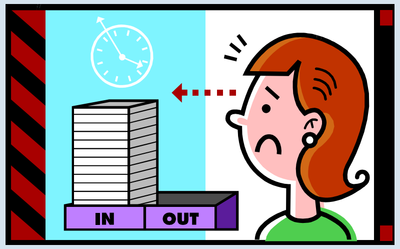

What does the user need to do? He starts at, say, line 142 and traces back to see if a bug is possible given what's happening.

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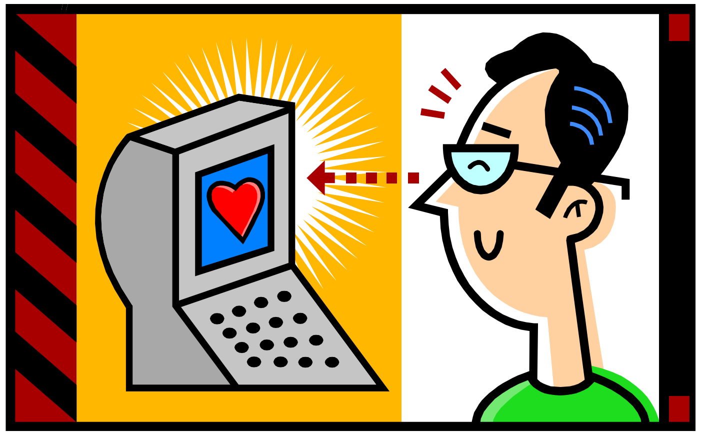
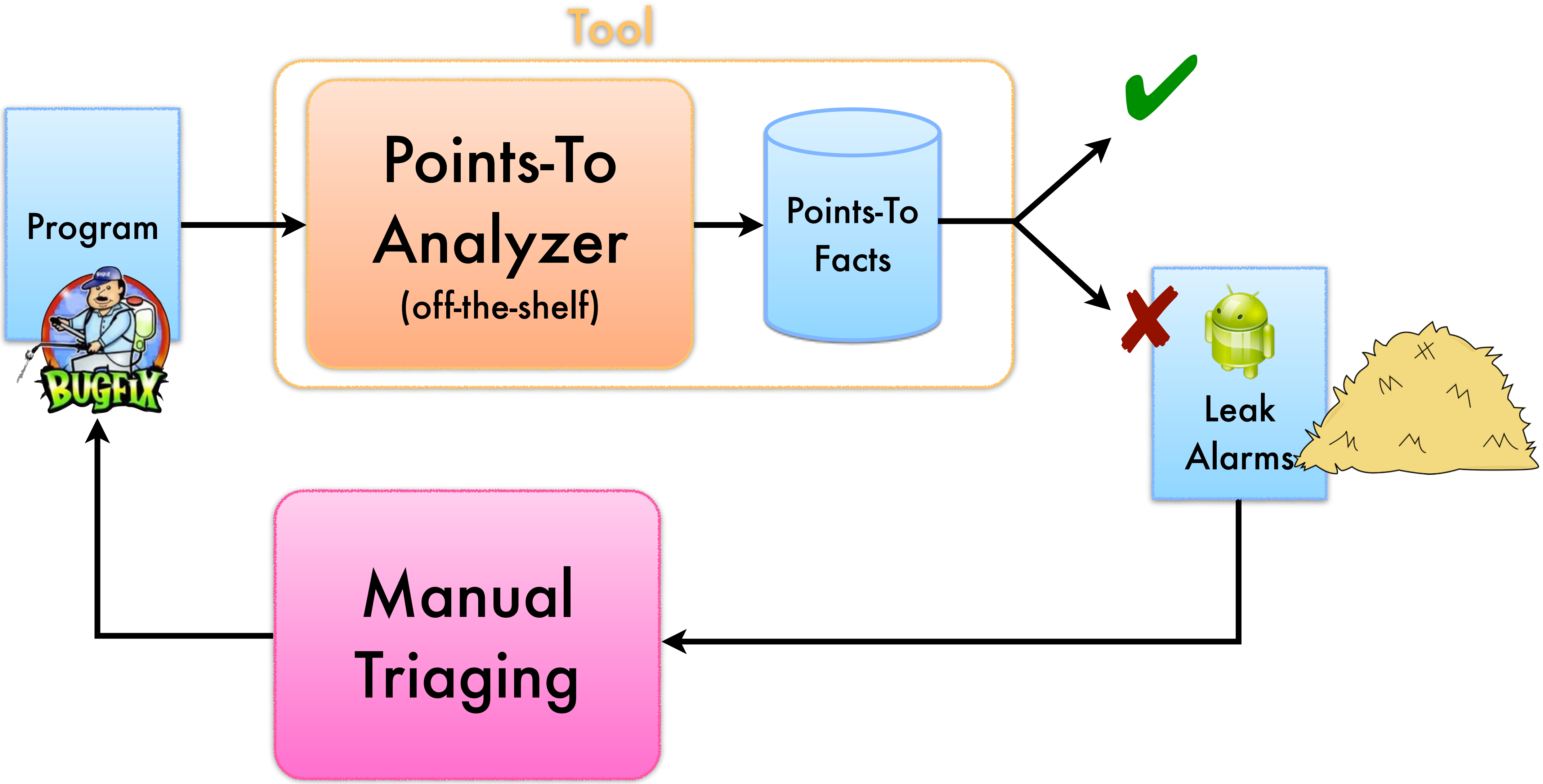


If we filter most false alarms, the user can triage more quickly and get to true bugs earlier (without frustration).

Roadmap: Thresher **filters** out false alarms by refuting them one-by-one.



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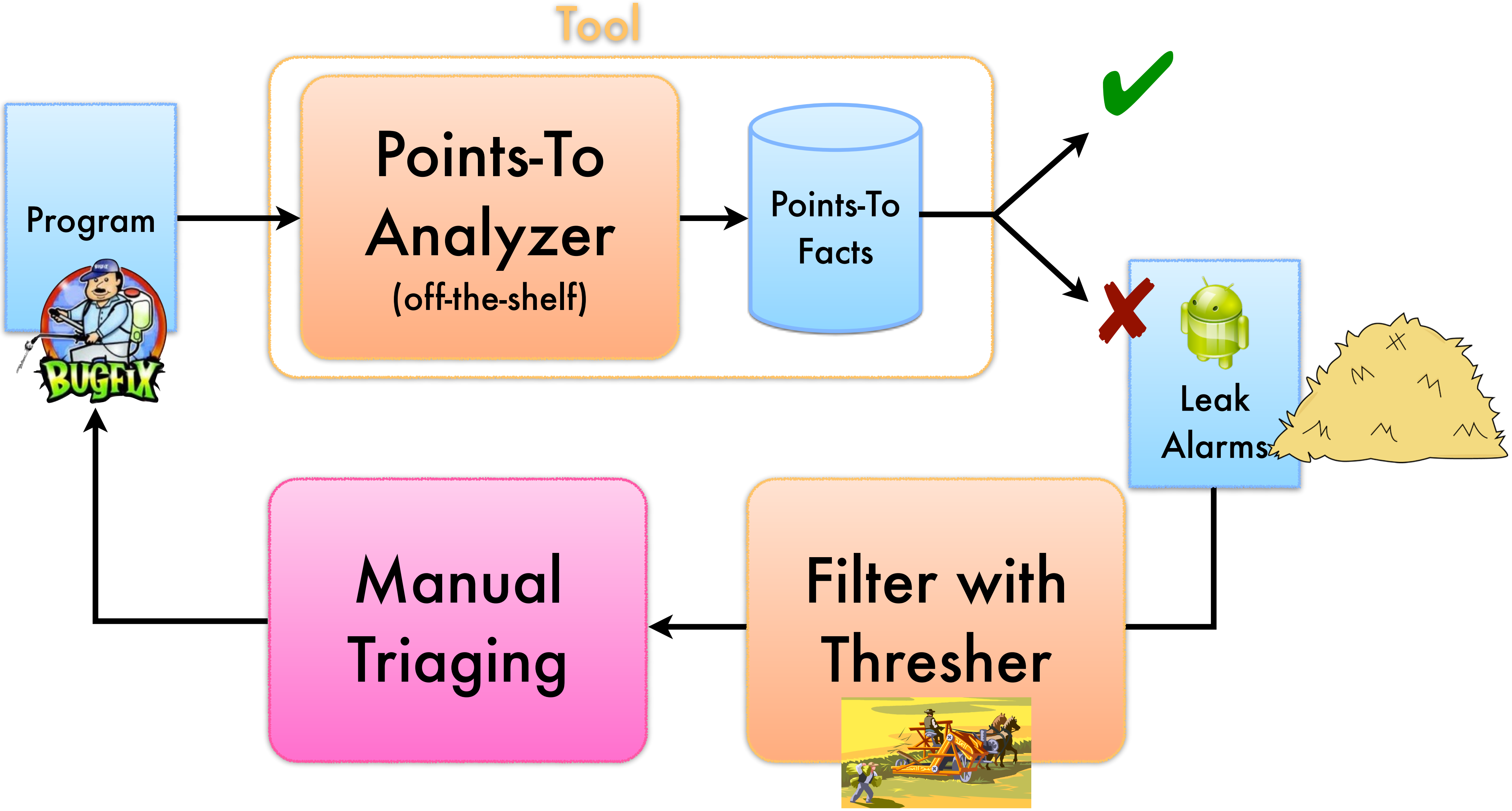

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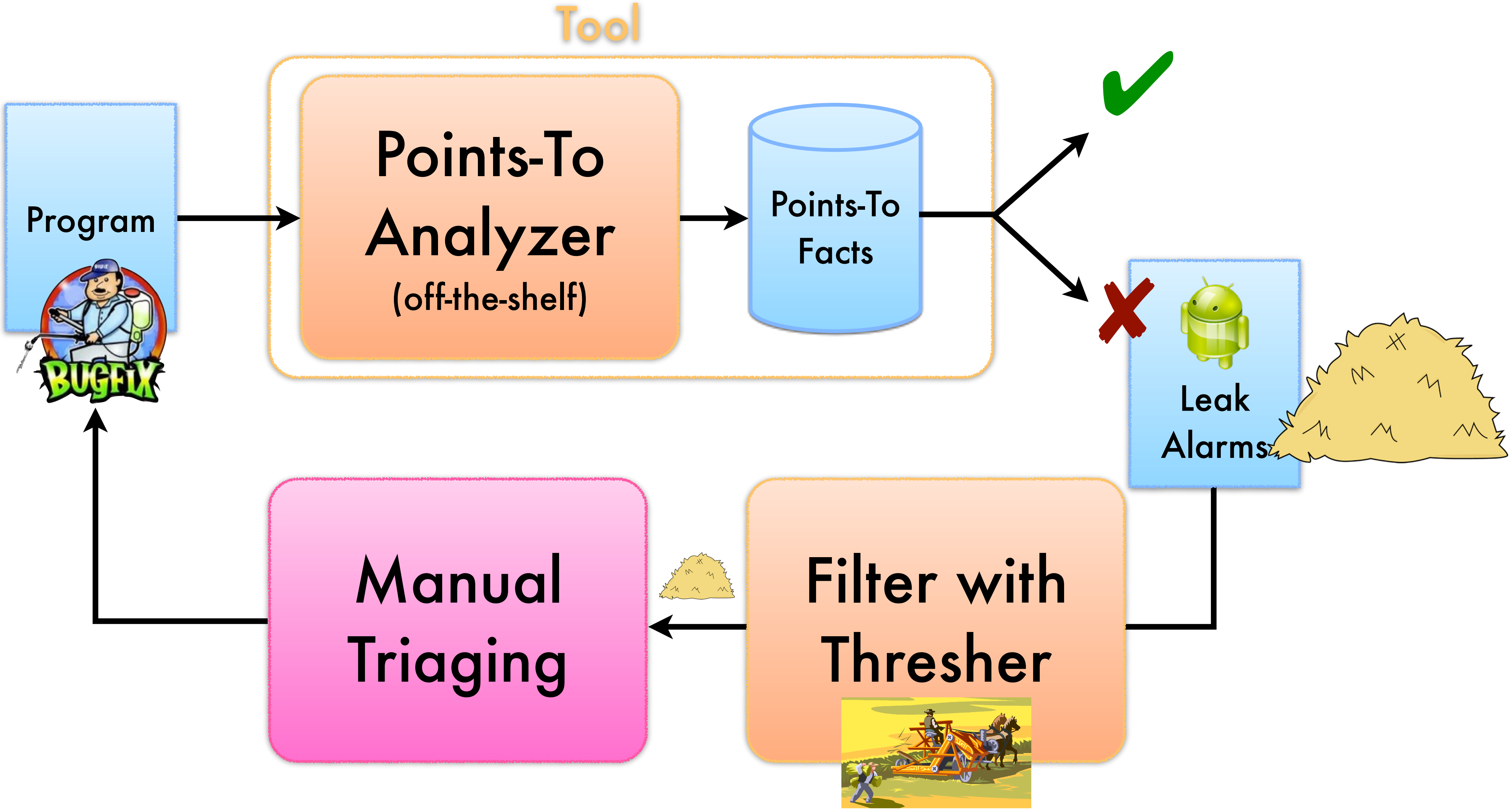

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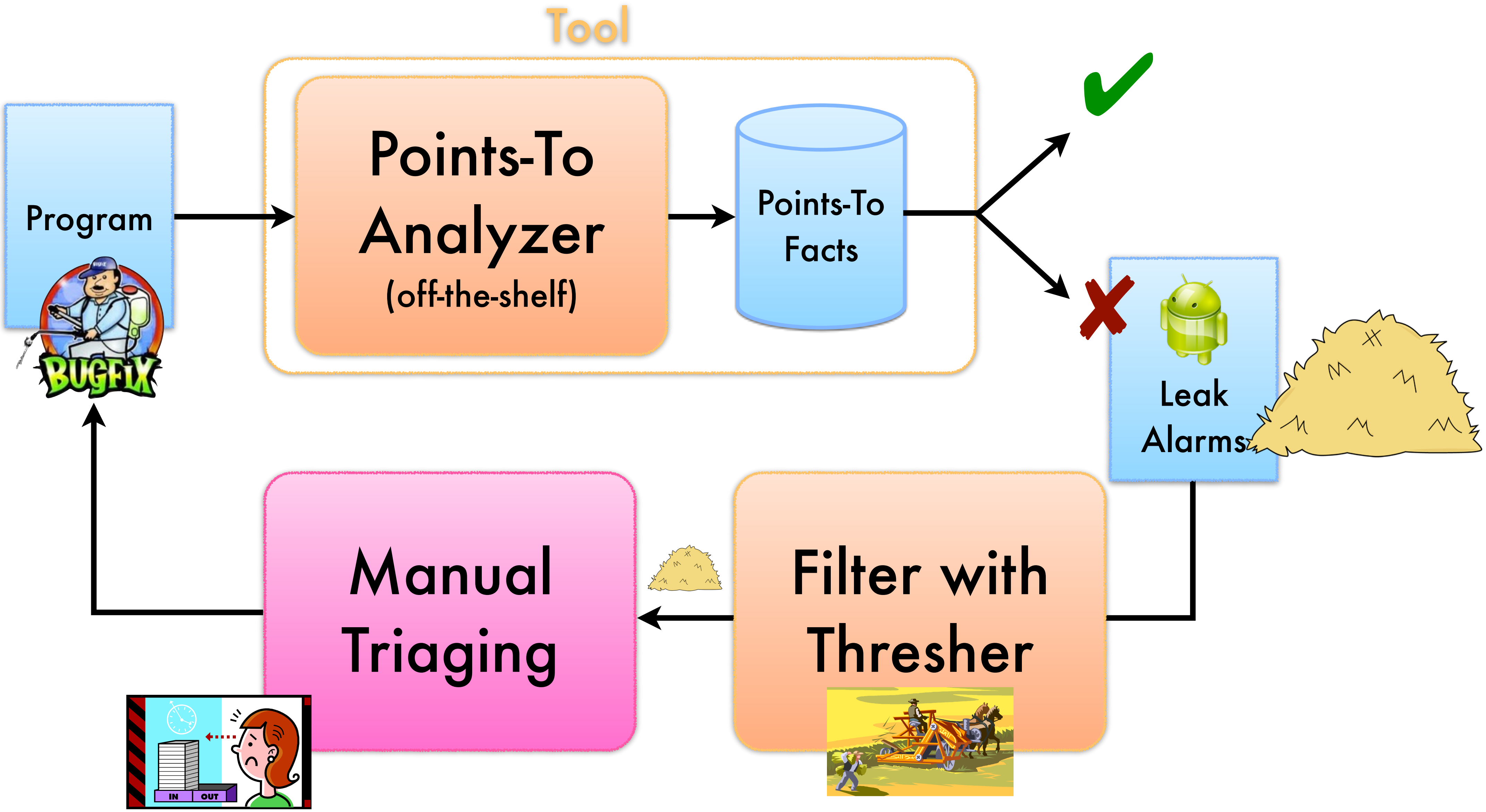

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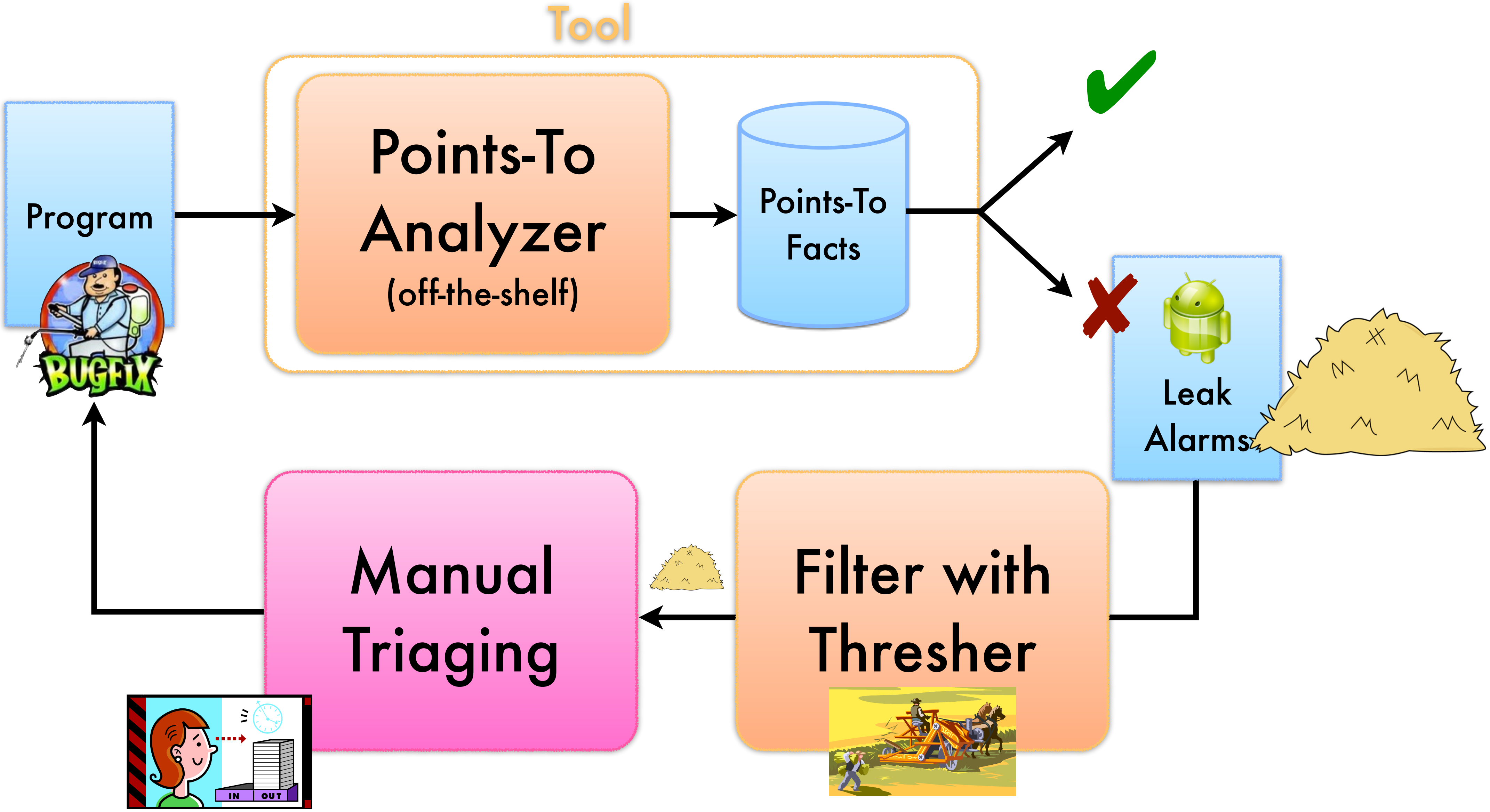

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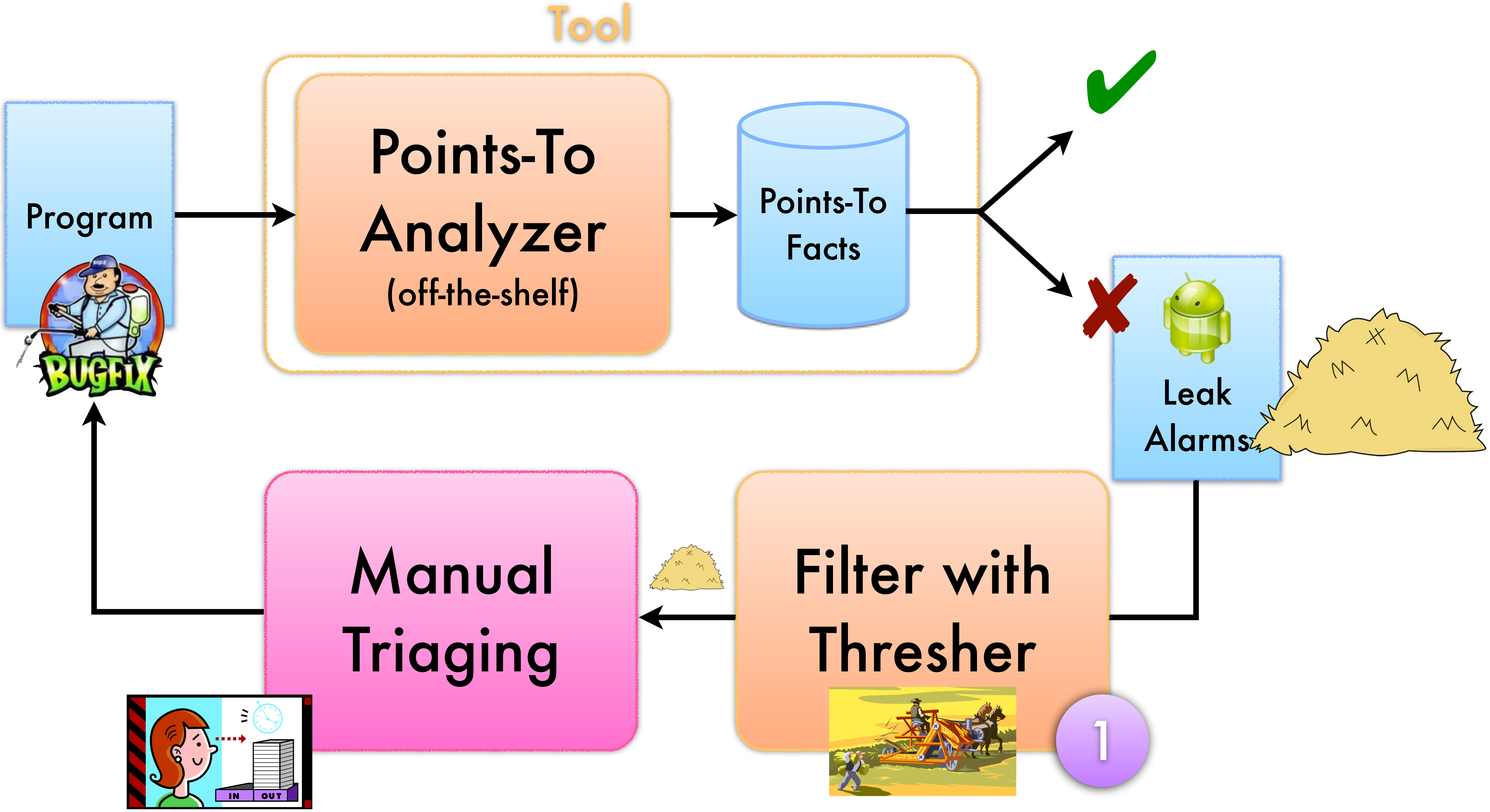
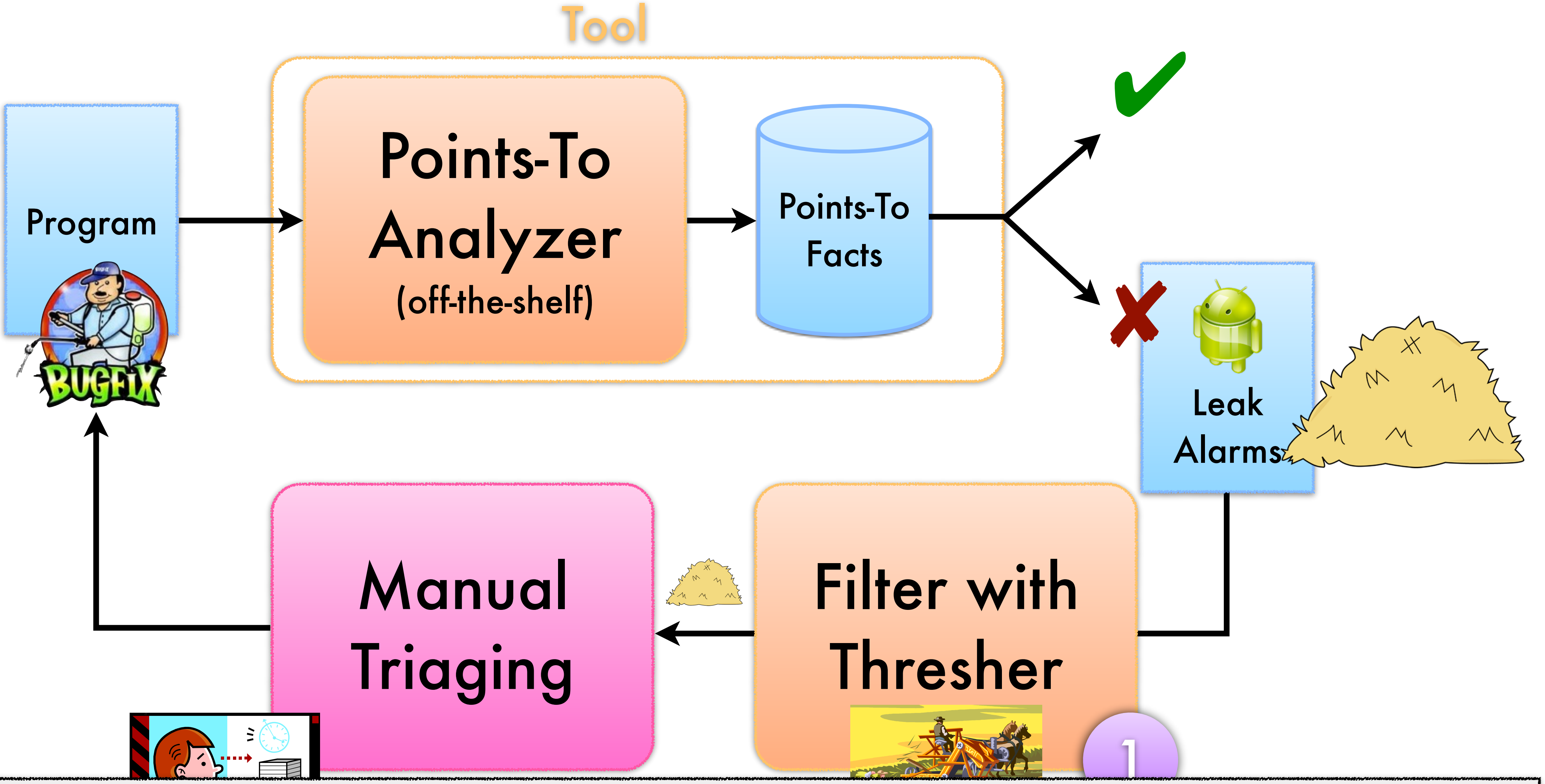


Idea 1: Refute points-to on-demand with second precise "filter" analysis

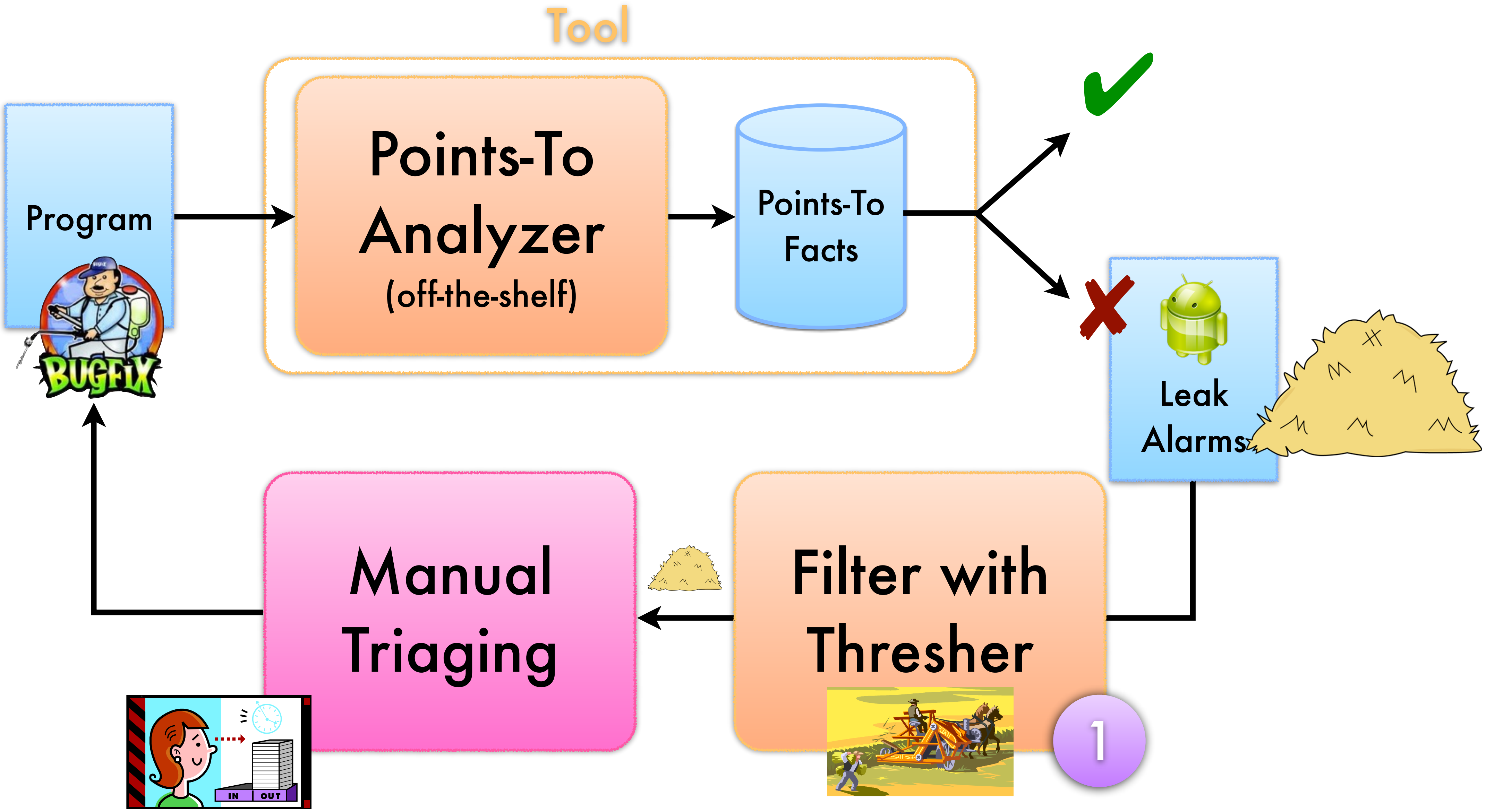
Roadmap: Thresher **filters** out false alarms by refuting them one-by-one.



*-sensitive, strong updates (separation logic) but over-approximate

Idea 1: Refute points-to on-demand with second precise “filter” analysis

Roadmap: Thresher filters out false alarms by refuting them one-by-one.



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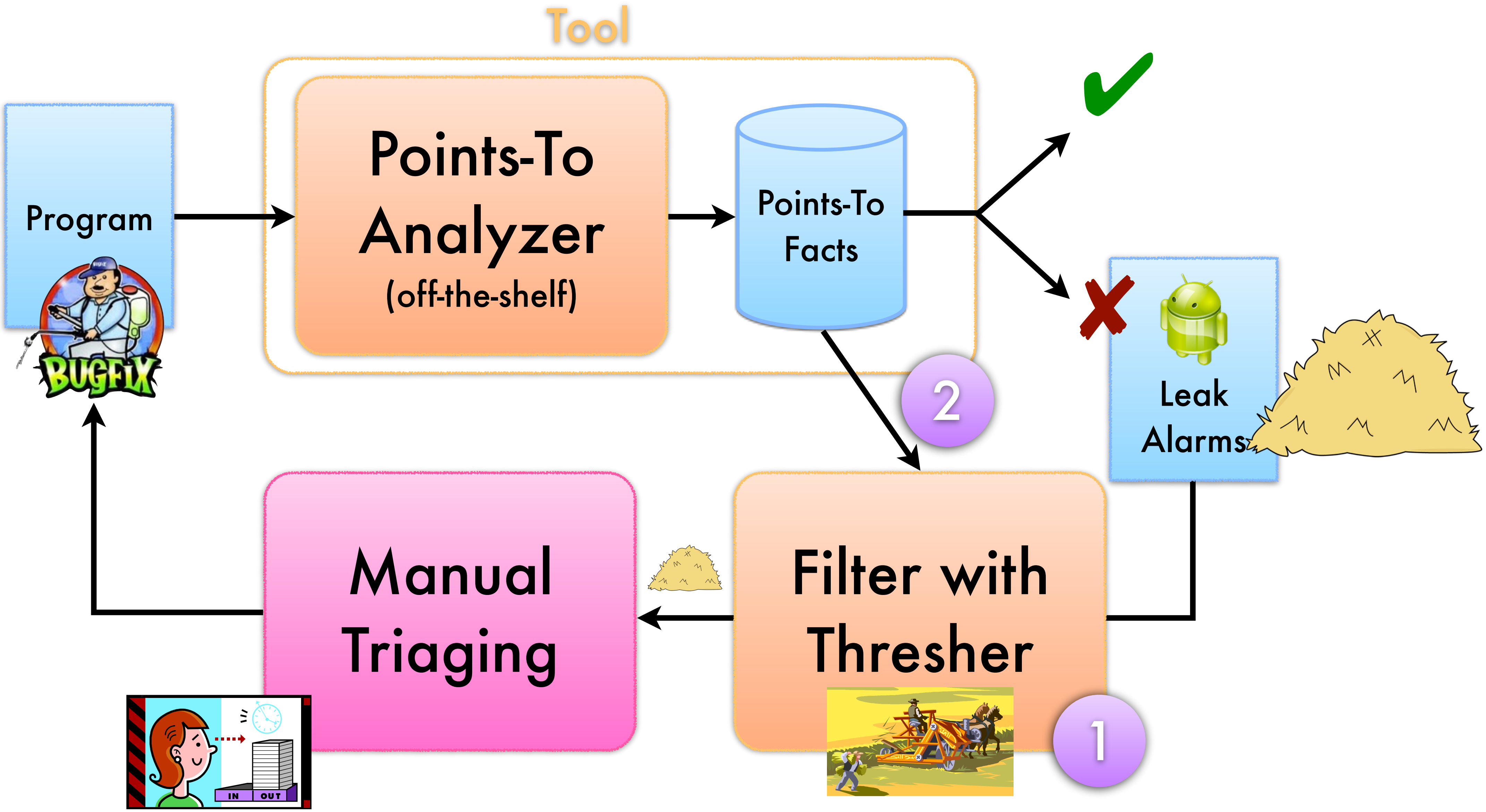


Tool

Program

Points-To Analyzer (off-the-shelf)

Points-To Facts

✓

✗

Leak Alarms

2

Manual Triaging

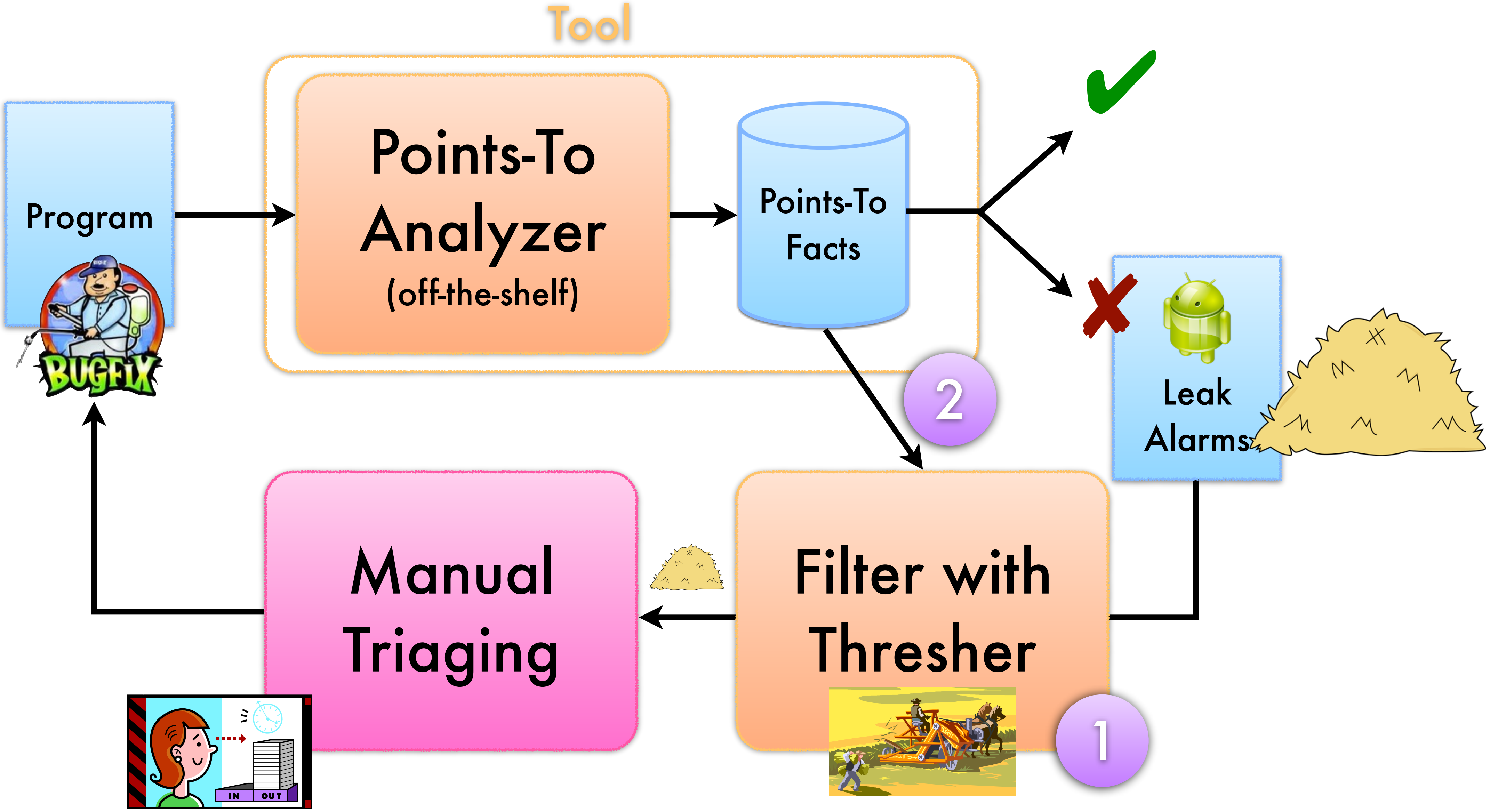
Filter with Thresher

1

Idea 1: Refute points-to on-demand with second precise “filter” analysis

Idea 2: Leverage the facts from the first analysis in the filter analysis to scale

Roadmap: Thresher **filters** out false alarms by refuting them one-by-one.

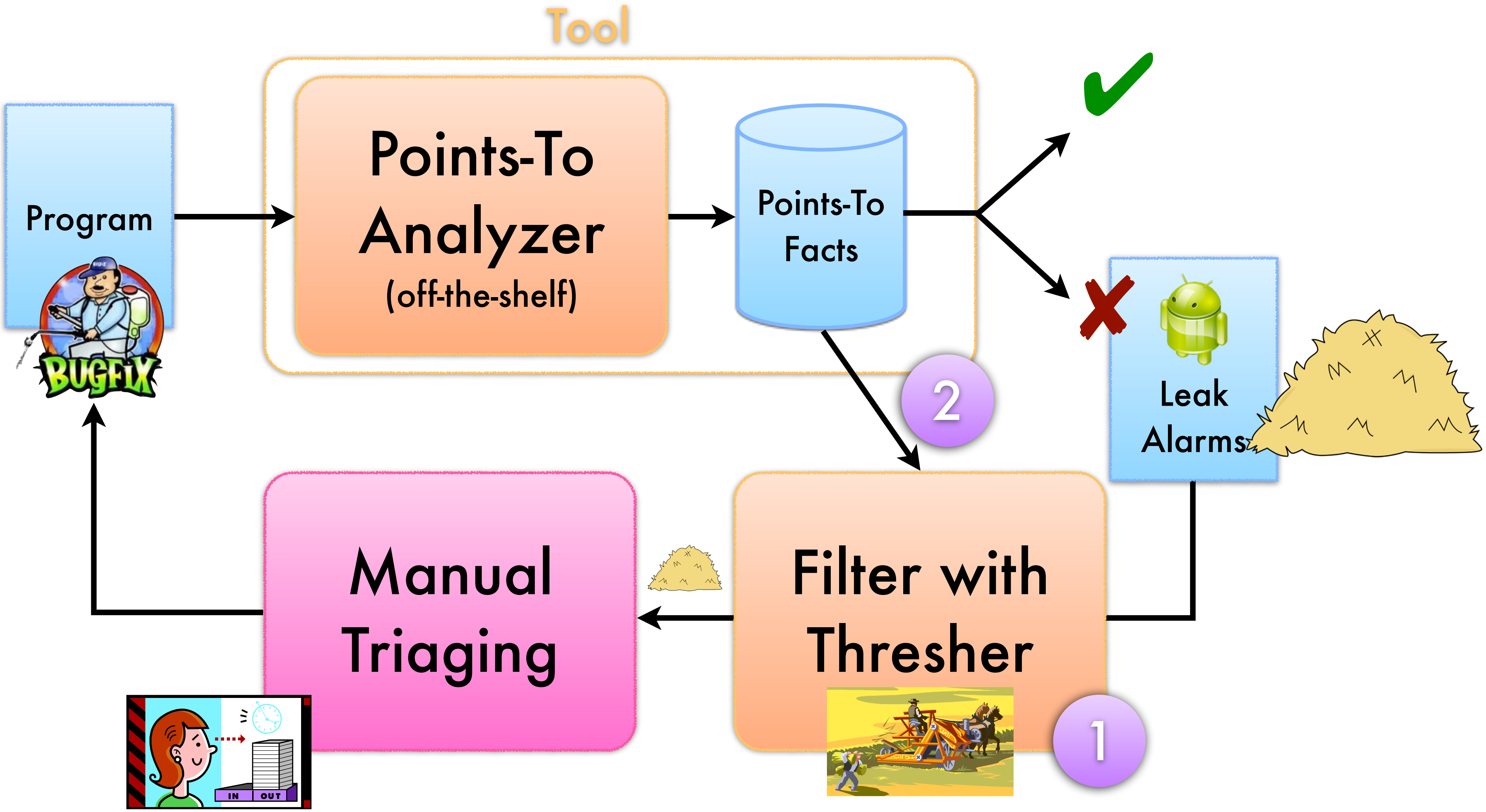


Idea 1: Refute points-to on-demand with second precise "filter" analysis

"**from** constraints" to reduce with the points-to domain

Idea 2: Leverage the facts from the first analysis in the filter analysis to scale

Roadmap: Thresher filters out false alarms by refuting them one-by-one.



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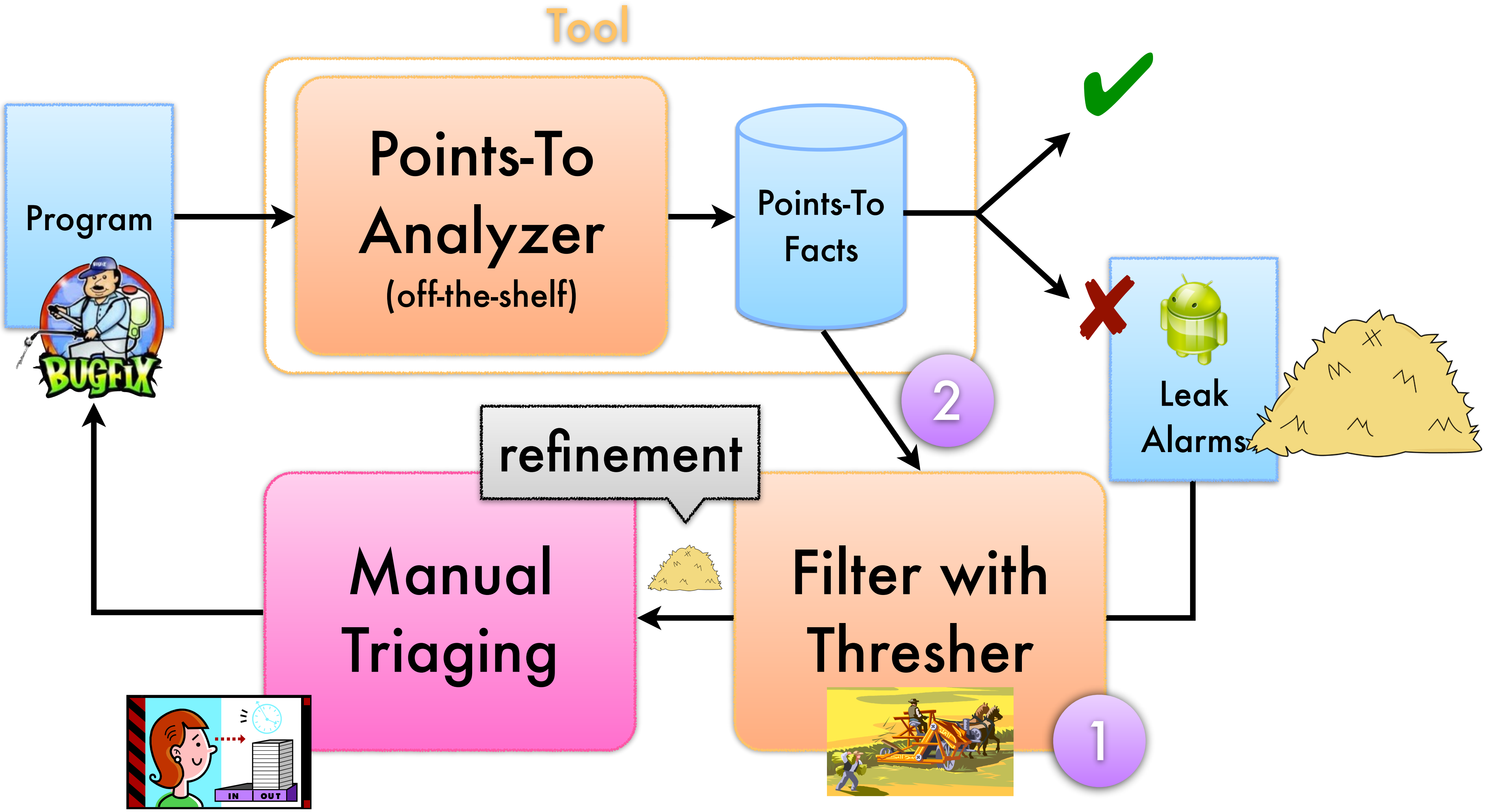

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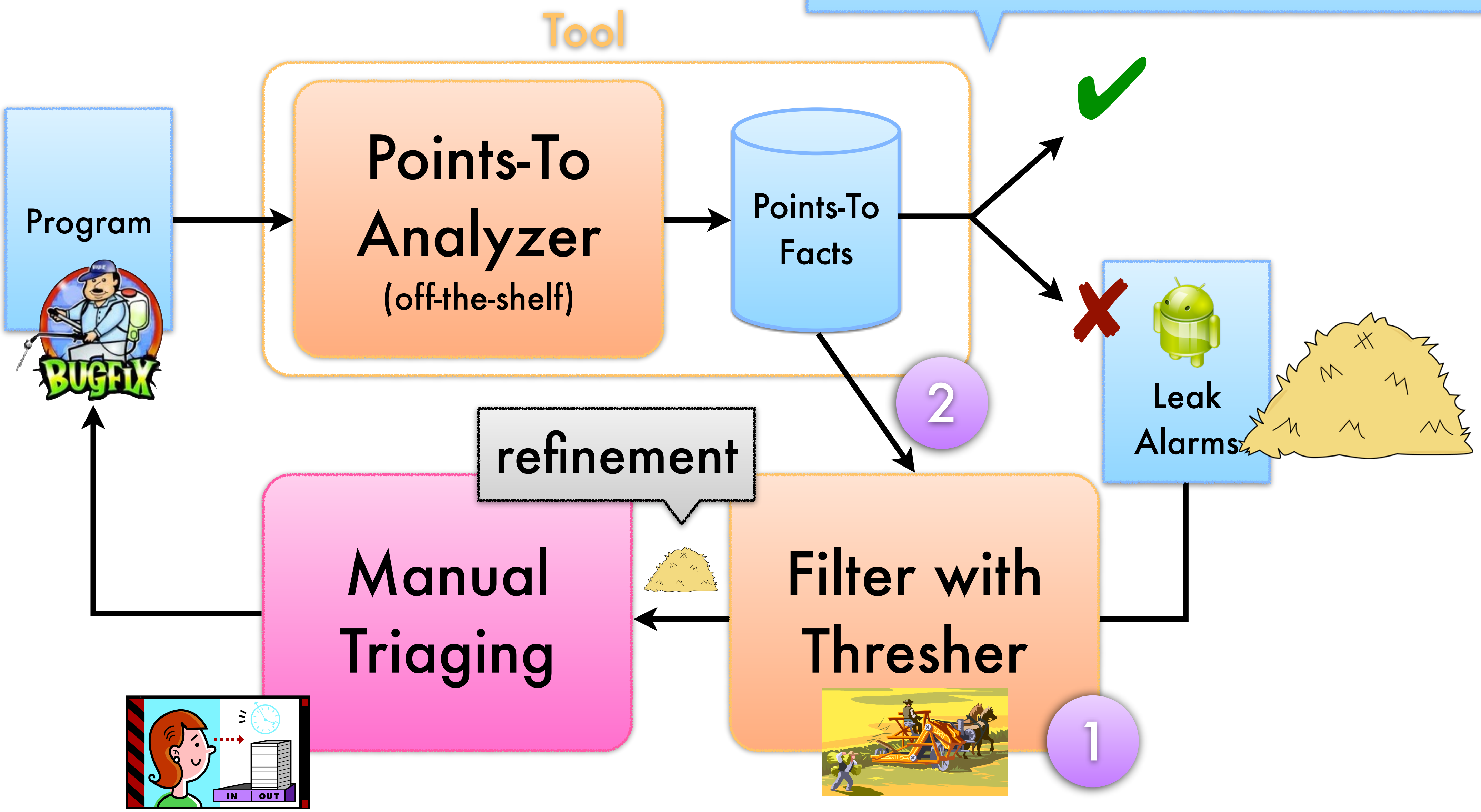
Roadmap: Thresher filters out false a refuting them one-by-one.

Related: Staged analysis
[Fink, Yahav, Dor, Ramalingam, Geay (2006)]



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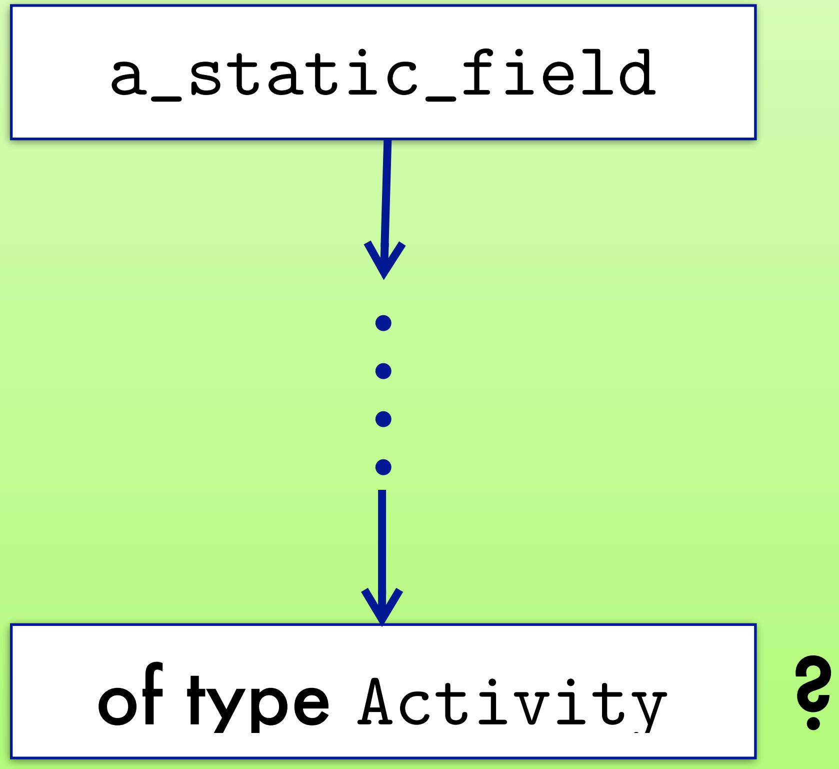
Idea 2: Leverage the facts from the first analysis in the filter analysis to scale

A top-level filter:
Filter leak alarms by refuting points-to edges

1

Is there a program execution where at some time

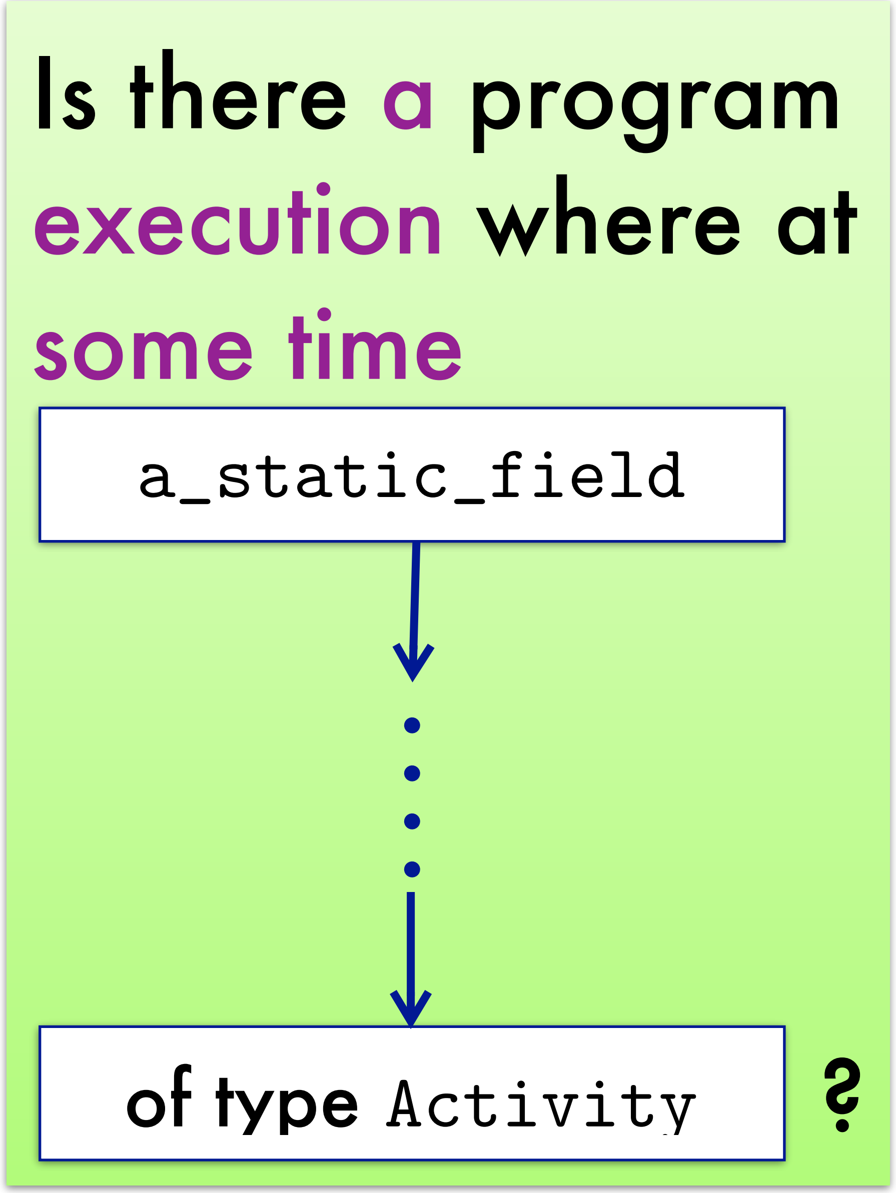


a_static_field

of type Activity ?

A top-level filter:
Filter leak alarms by refuting points-to edges

1



Is there a program execution where at some time

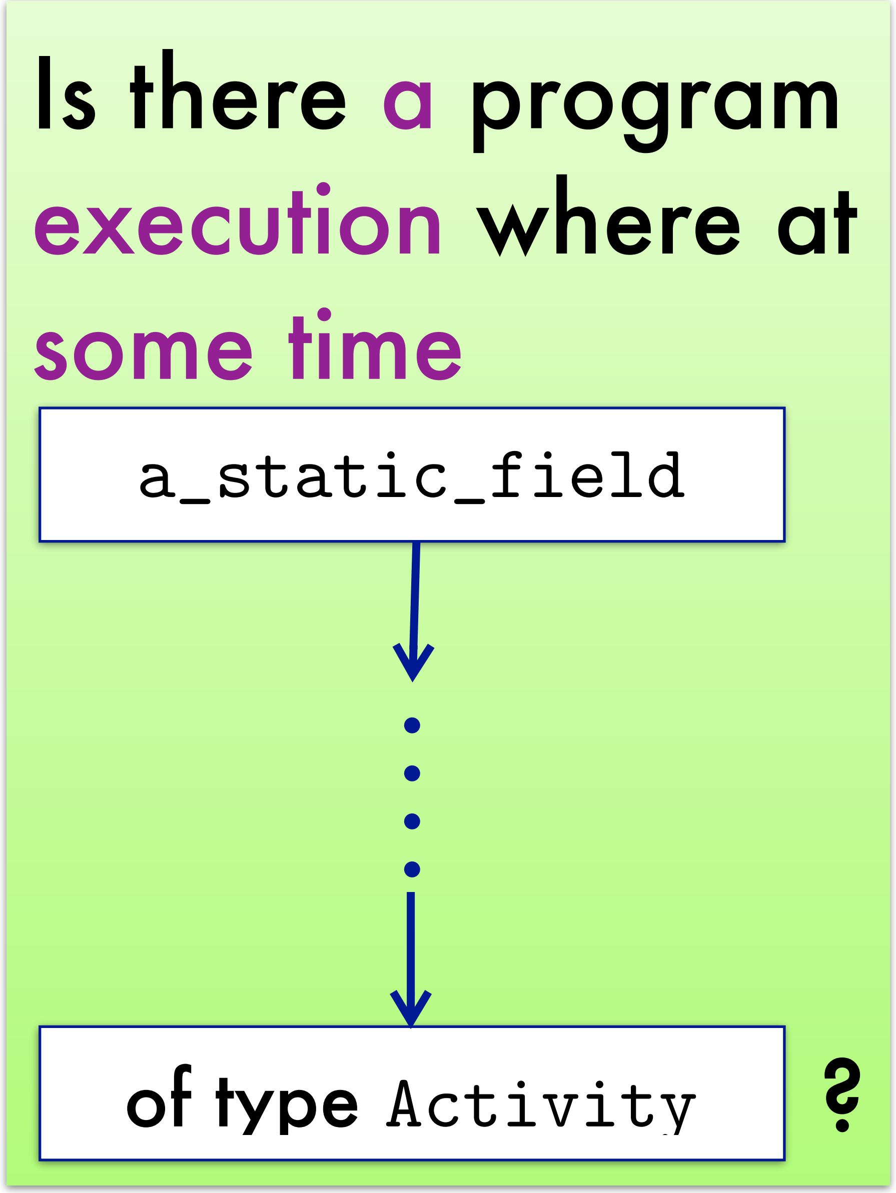
`a_static_field`

of type `Activity` ?

Select a points-to edge in the path

A top-level filter:
Filter leak alarms by refuting points-to edges

1



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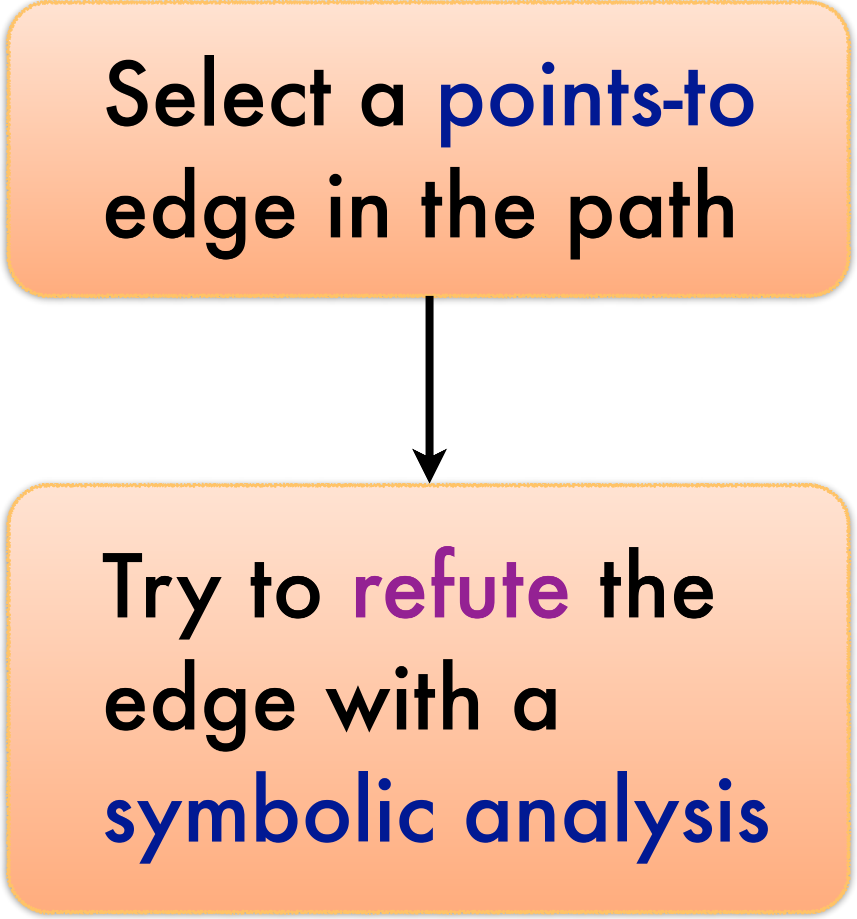

Select a points-to edge in the path

Try to refute the edge with a symbolic analysis

A top-level filter: Filter leak alarms by refuting points-to edges

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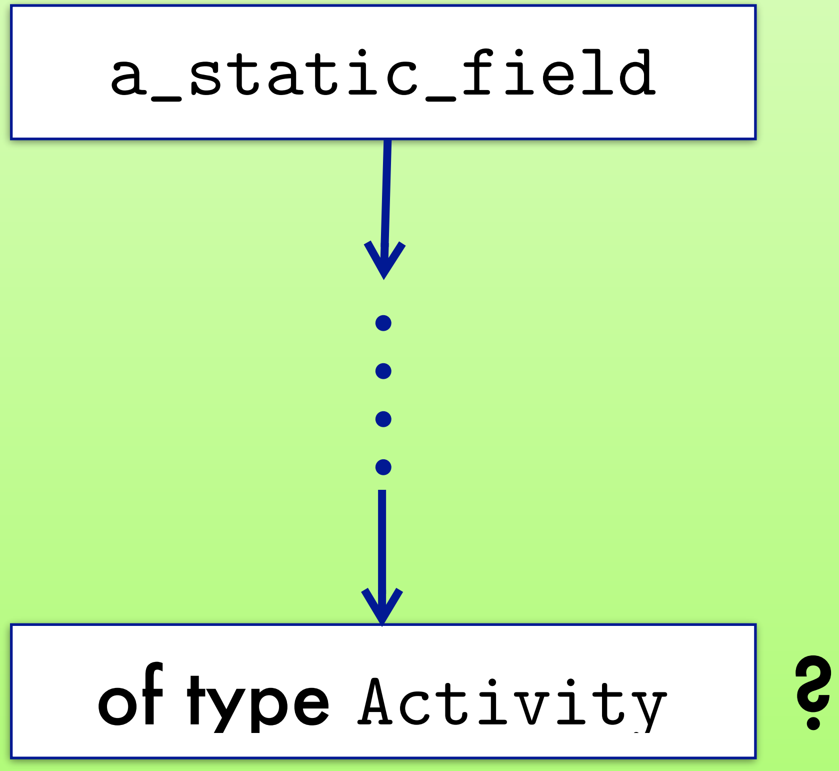

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⋮

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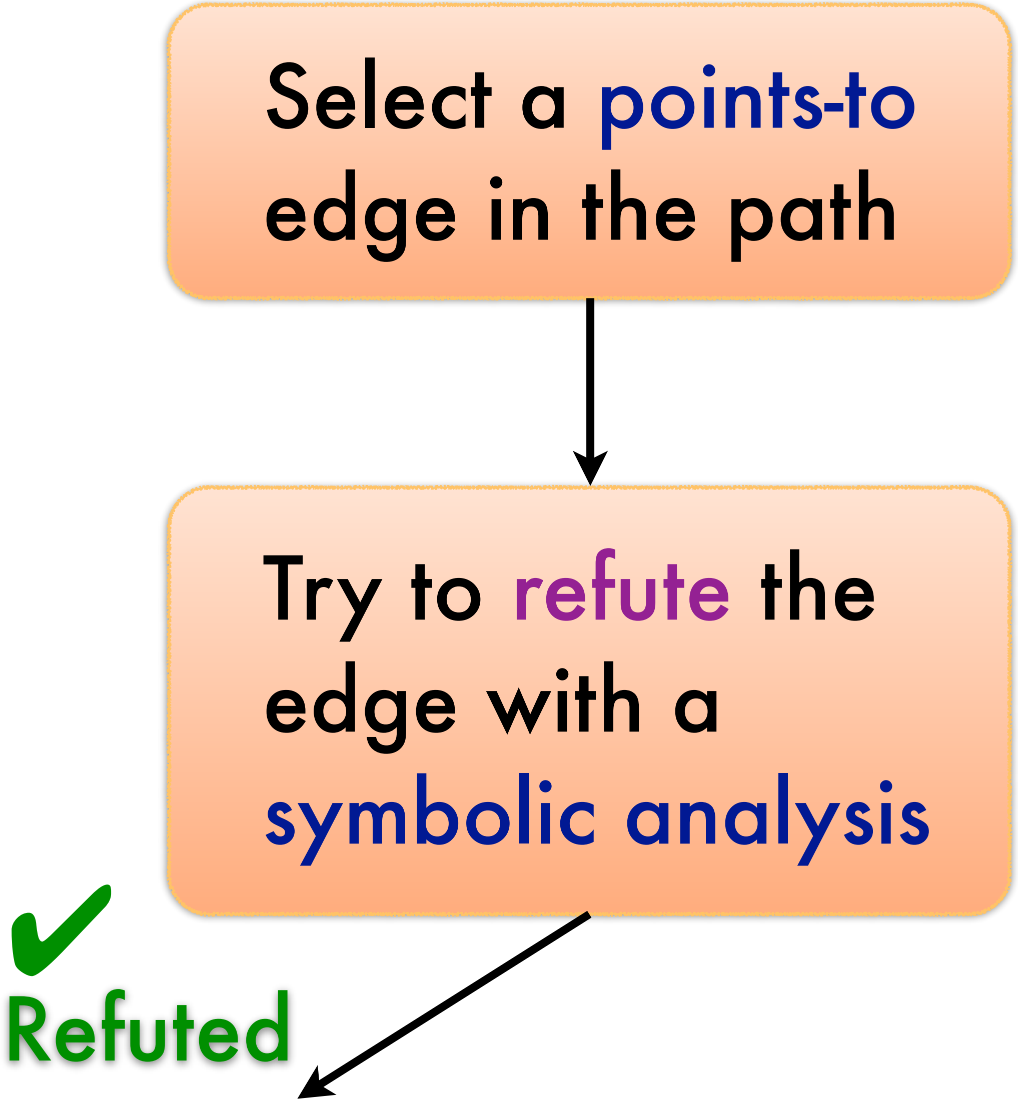

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✔ Refuted

A top-level filter:
Filter leak alarms by refuting points-to edges

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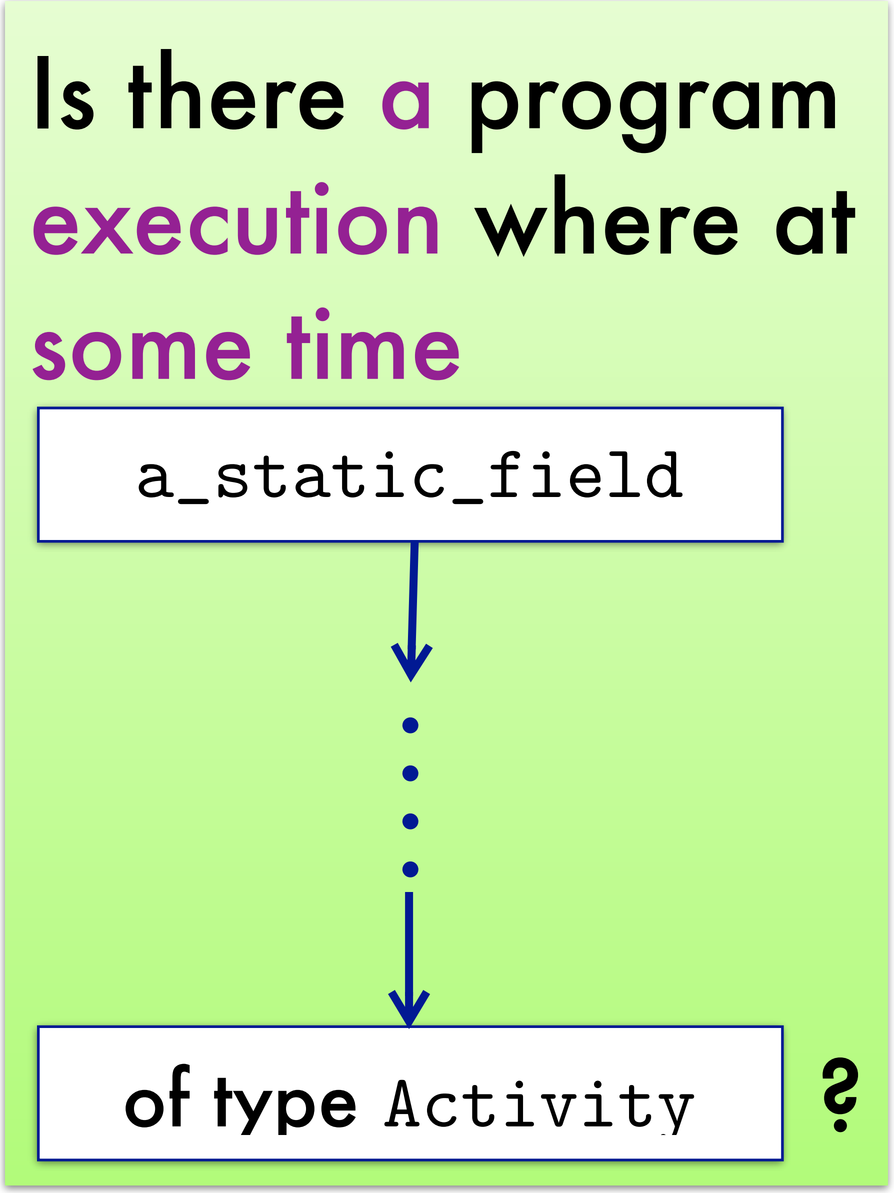

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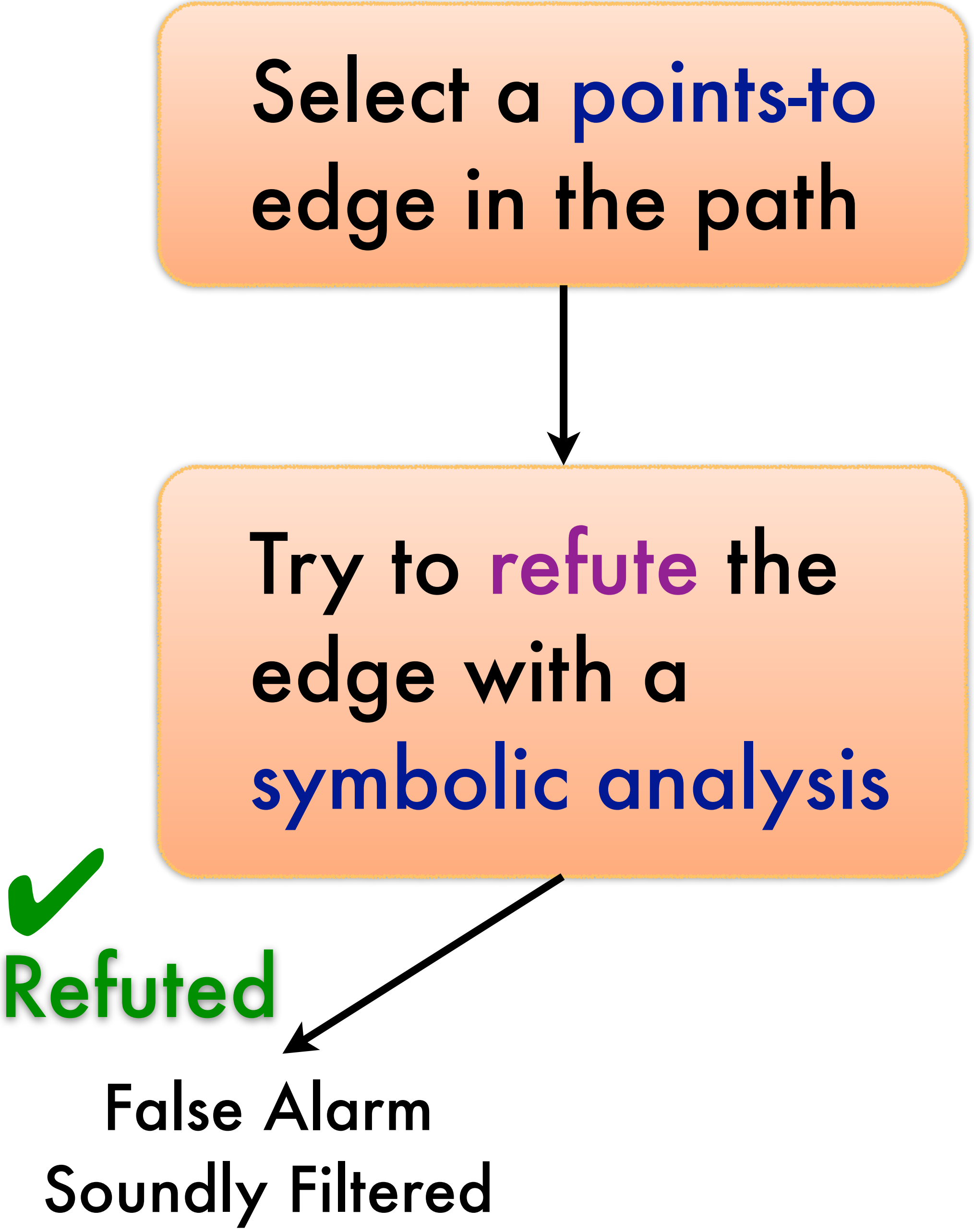


Select a points-to edge in the path

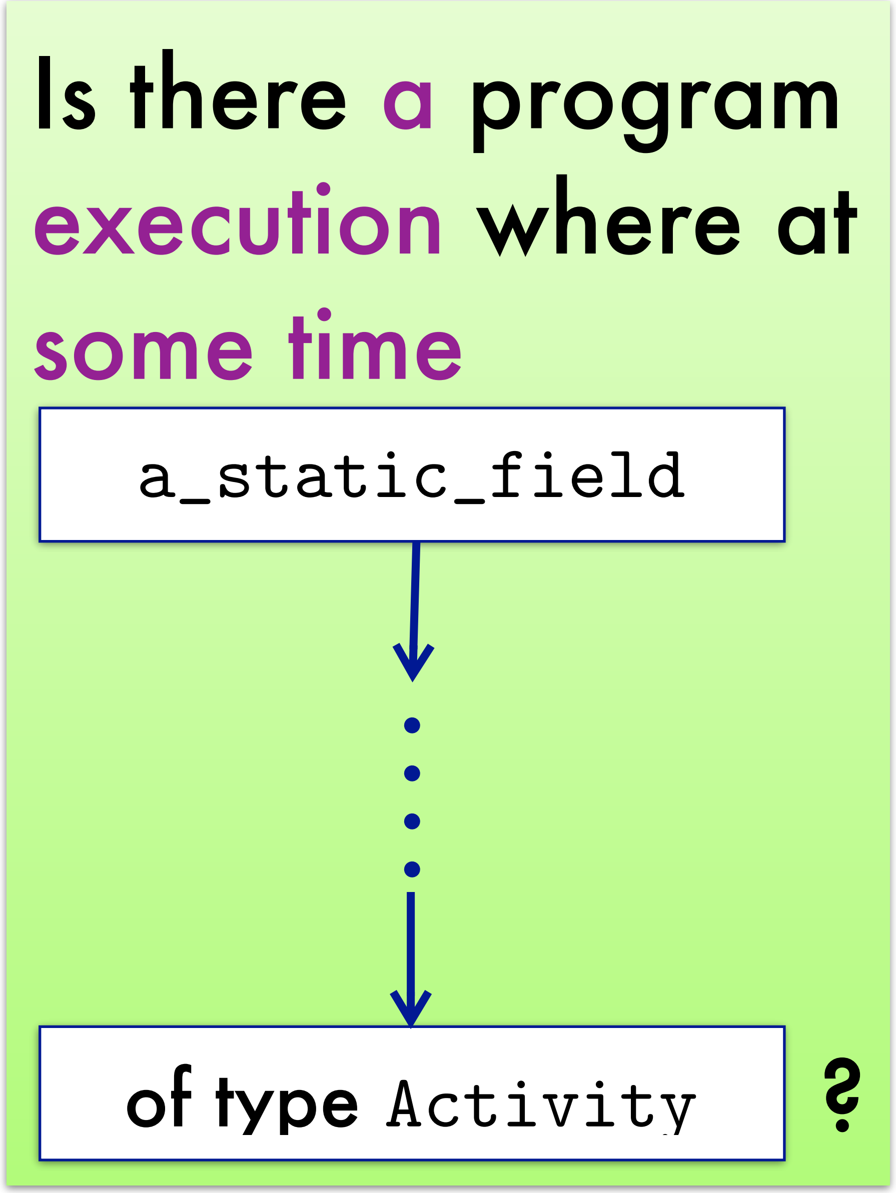
Try to refute the edge with a symbolic analysis

✓ Refuted

False Alarm
Soundly Filtered

A top-level filter:
Filter leak alarms by refuting points-to edges

1



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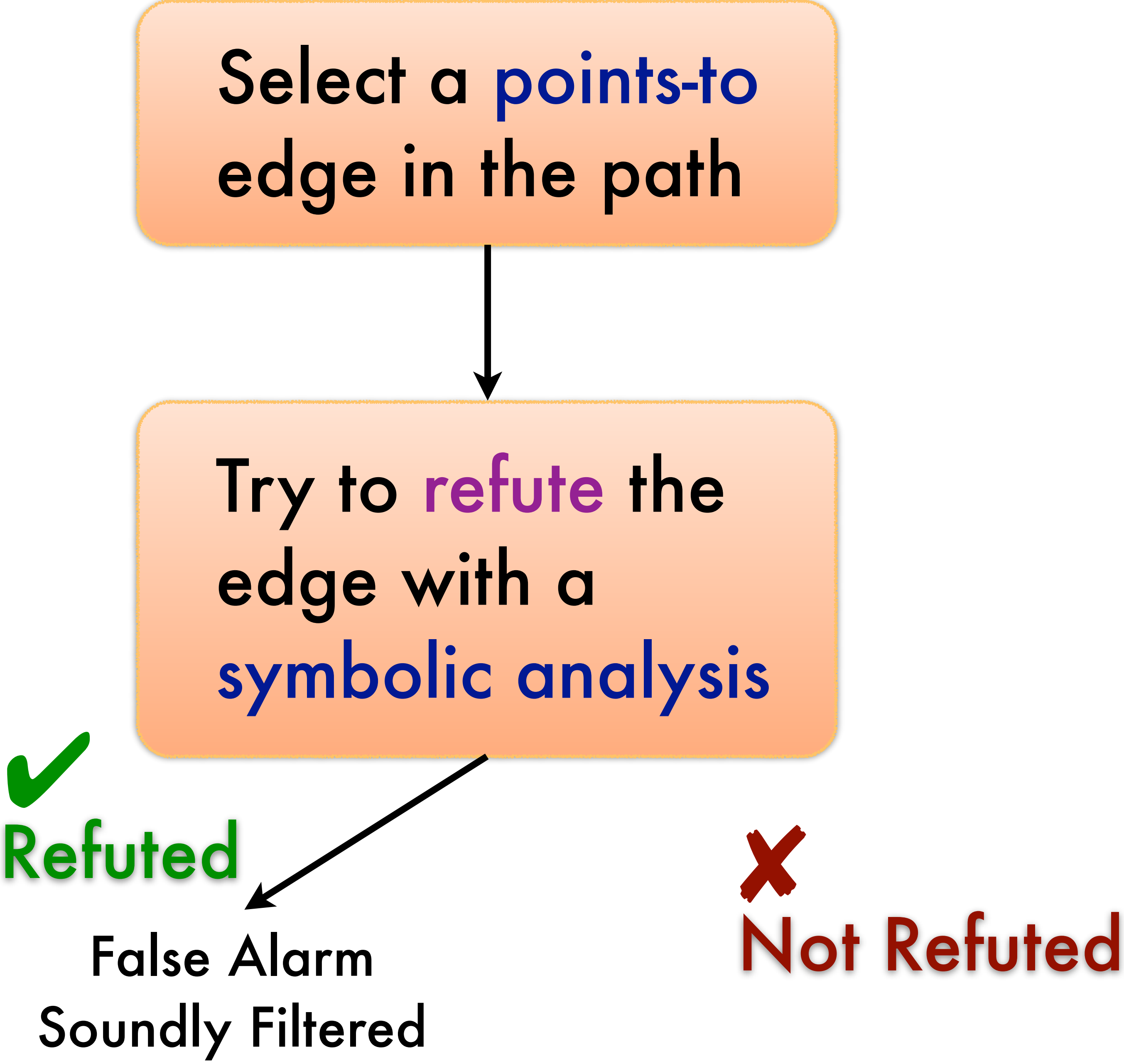

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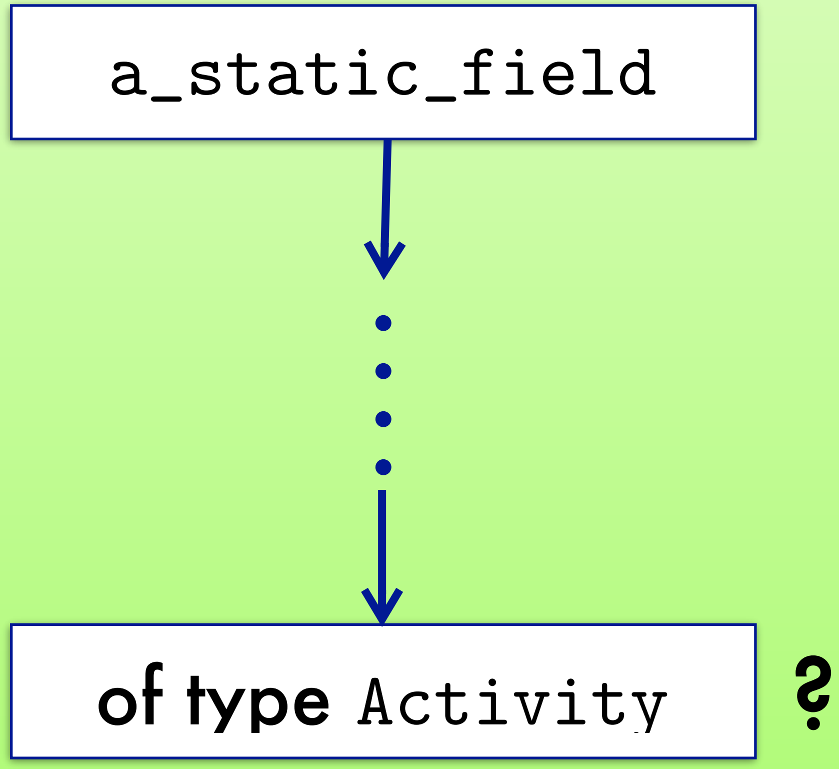

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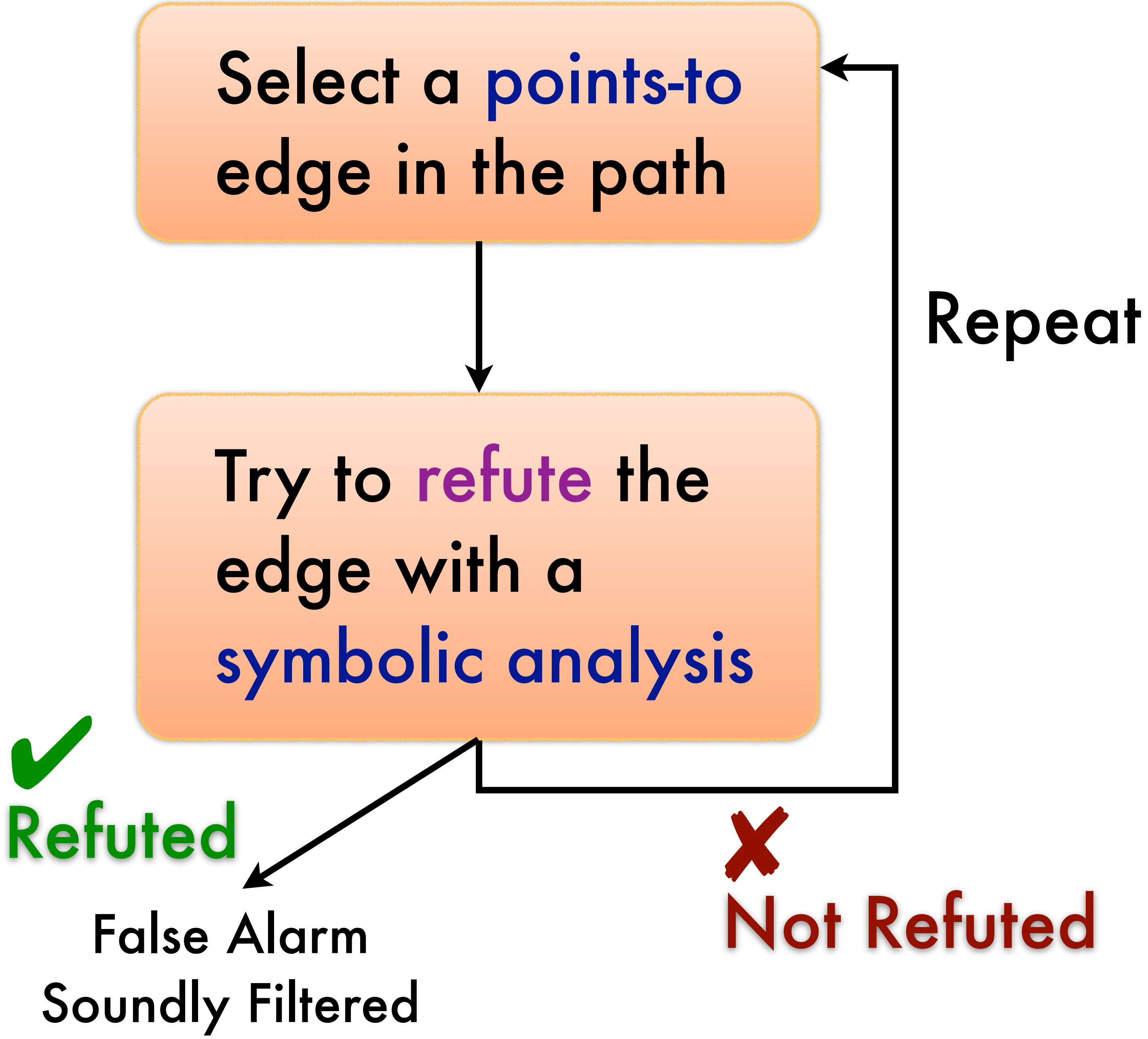

Select a points-to edge in the path

Try to refute the edge with a symbolic analysis

Repeat

✔ Refuted

False Alarm
Soundly Filtered

✘ Not Refuted

A top-level filter:
Filter leak alarms by refuting points-to edges

1

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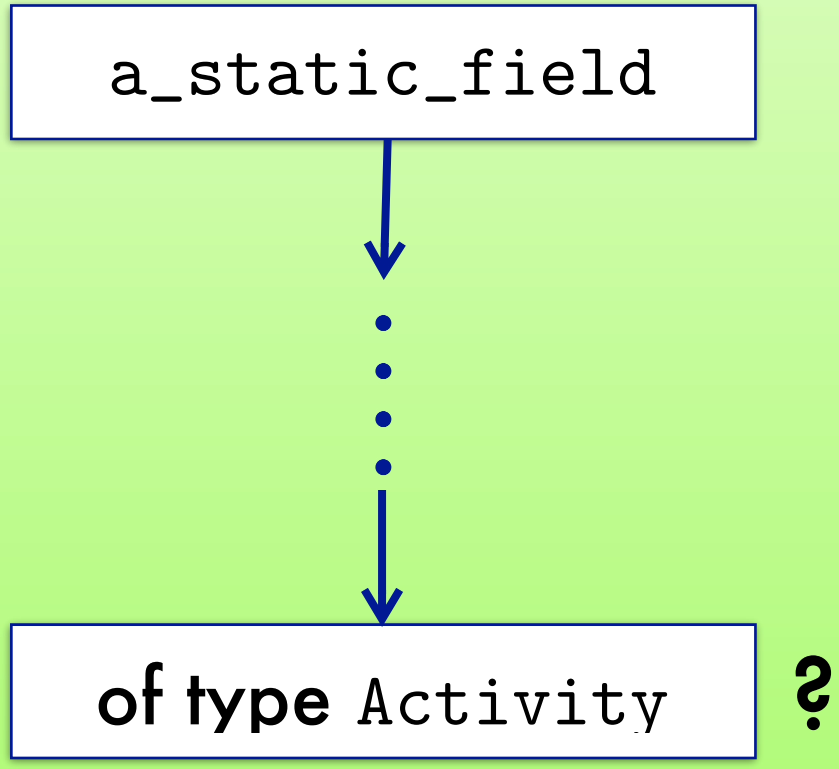

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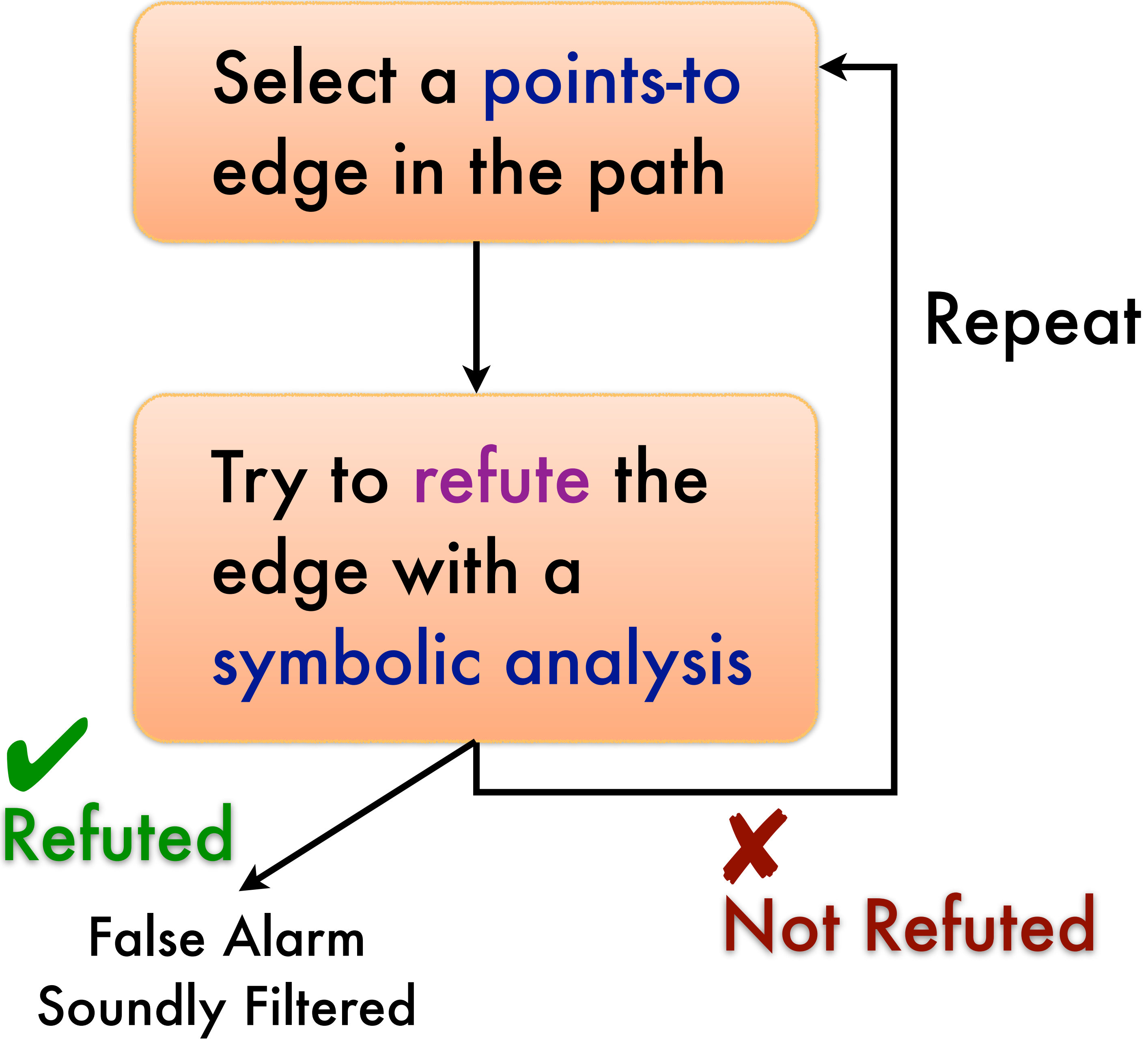

Select a points-to edge in the path

Try to refute the edge with a symbolic analysis

Repeat

✔ Refuted

False Alarm
Soundly Filtered

✘ Not Refuted

Refutation: Derive a contradiction, that a points-to relation can't actually hold

Refuting a points-to edge: What are we up against?

1

```
class Vec {
  static Object[] EMPTY = new$_{\mathsf{arr}_0}$ Object[1]; ...
  Vec() { this.tbl = EMPTY; capacity initially empty }









}
```

Refuting a points-to edge: What are we up against?

1

Null object pattern: Should never be written to

```
class Vec
  static Object[] EMPTY = new_{arr_0} Object[1]; ...
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Refuting a points-to edge: What are we up against?

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class Vec
  static Object[] EMPTY = new$_{arr_0}$ Object[1]; ...
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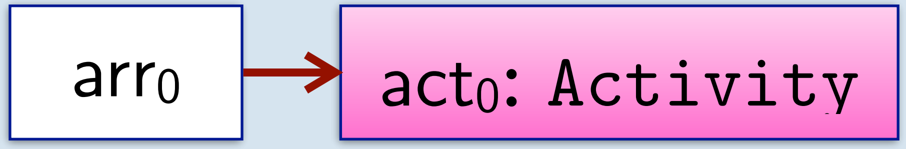
  void push(Object val) {
    if (need capacity) {
      this.tbl = new$_{arr_1}$ Object[more capacity];
      copy from old table
    }
    this.tbl[next slot] = val;
  }
}
```

Refuting a points-to edge: What are we up against?


arr$_0$ → act$_0$: Activity

1

Null object pattern: Should never be written to

```
class Vec
  static Object[] EMPTY = new$_{arr_0}$ Object[1]; ...
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```

Refuting a points-to edge: What are we up against?

Null object pattern: Should never be written to

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  static Object[] EMPTY = new_arr0 Object[1]; ...
  Vec() { this.tbl = EMPTY; capacity initially empty }

  void push(Object val) {
    if (need capacity) {
      this.tbl = new_arr1 Object[more capacity];
      copy from old table
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    this.tbl[next slot] = val;
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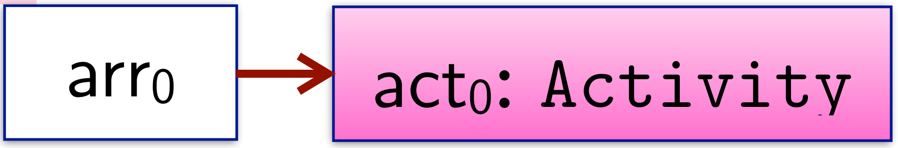
```



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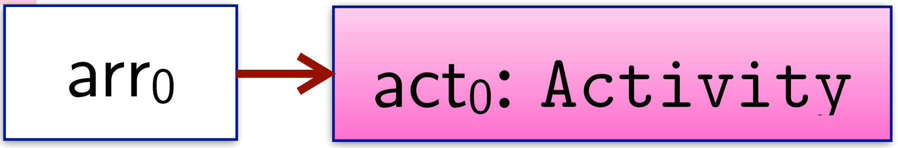

Refuting a points-to edge: What are we up against?

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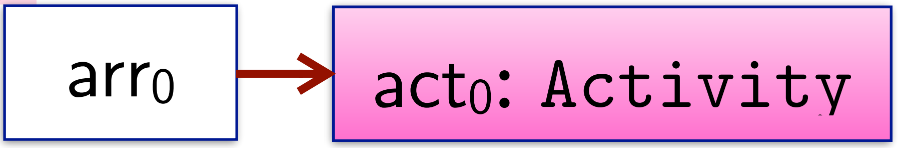
      copy from old table
    }
    this.tbl[next slot] = val;
  }
}
```

Null object pattern: Should never be written to

Need interprocedural path-sensitivity



arr_0

act_0: Activity

Refuting a points-to edge: What are we up against?

1

```
class Vec
  static Object[] EMPTY = new_arr0 Object[1]; ...
  Vec() { this.tbl = EMPTY; capacity initially empty }

  void push(Object
    if (need capacity) {
      this.tbl = new_arr1 Object[more capacity];
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```

Null object pattern: Should never be written to

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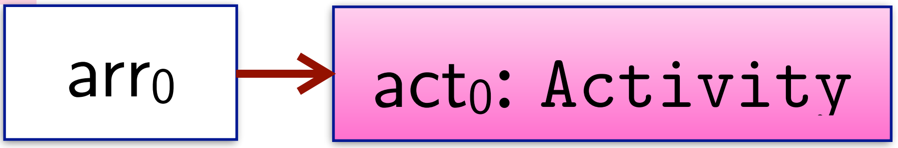

Refuting a points-to edge: What are we up against?

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    }
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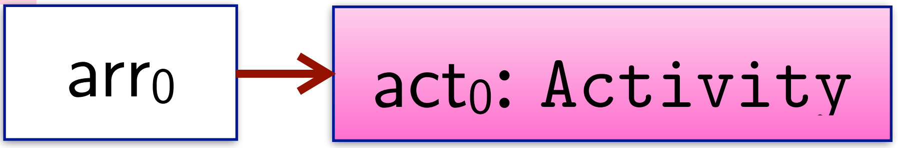
```

Need interprocedural path-sensitivity

Need strong updates



A refutation analysis: Try to derive a contradiction with a backwards symbolic analysis

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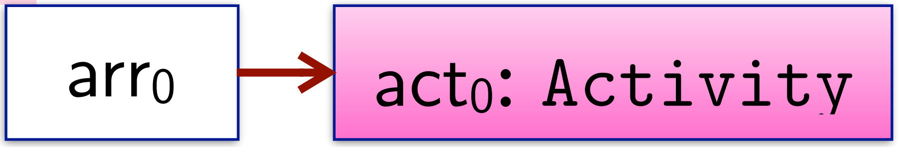

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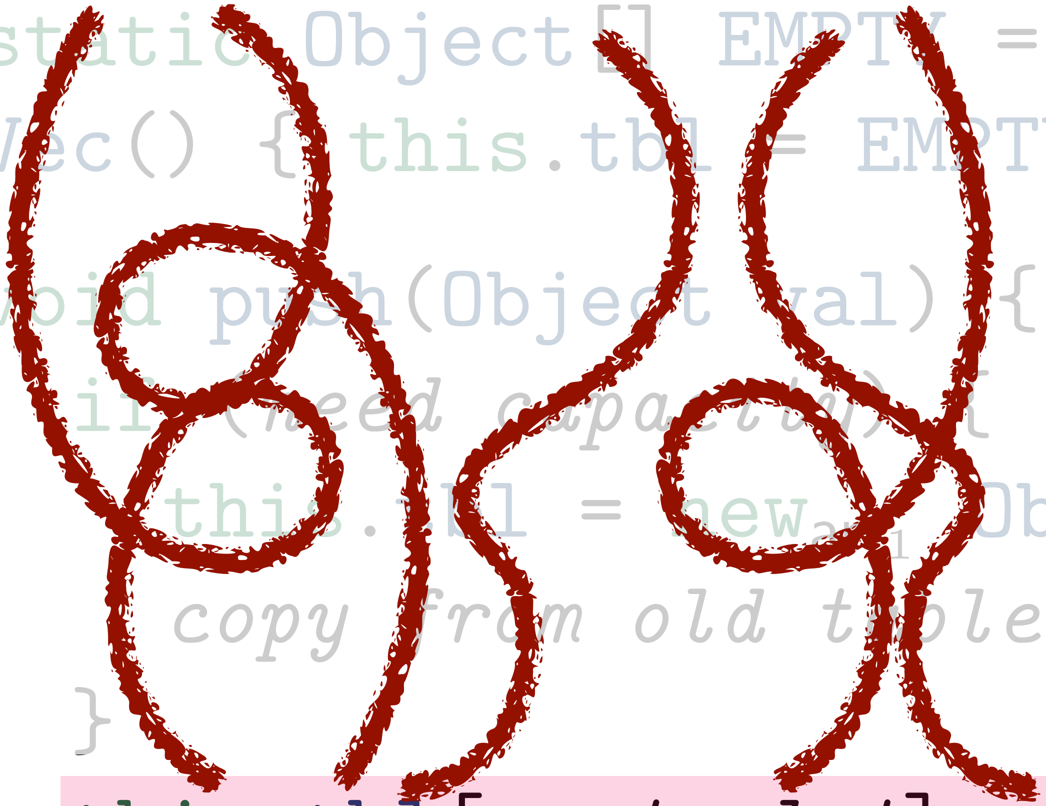
      copy from old table
    }
    this.tbl[next slot] = val;
  }
}
```

$arr_0 \cdot$[-] $\mapsto act_0 *$ true

A refutation analysis: Try to derive a contradiction with a backwards symbolic analysis

1



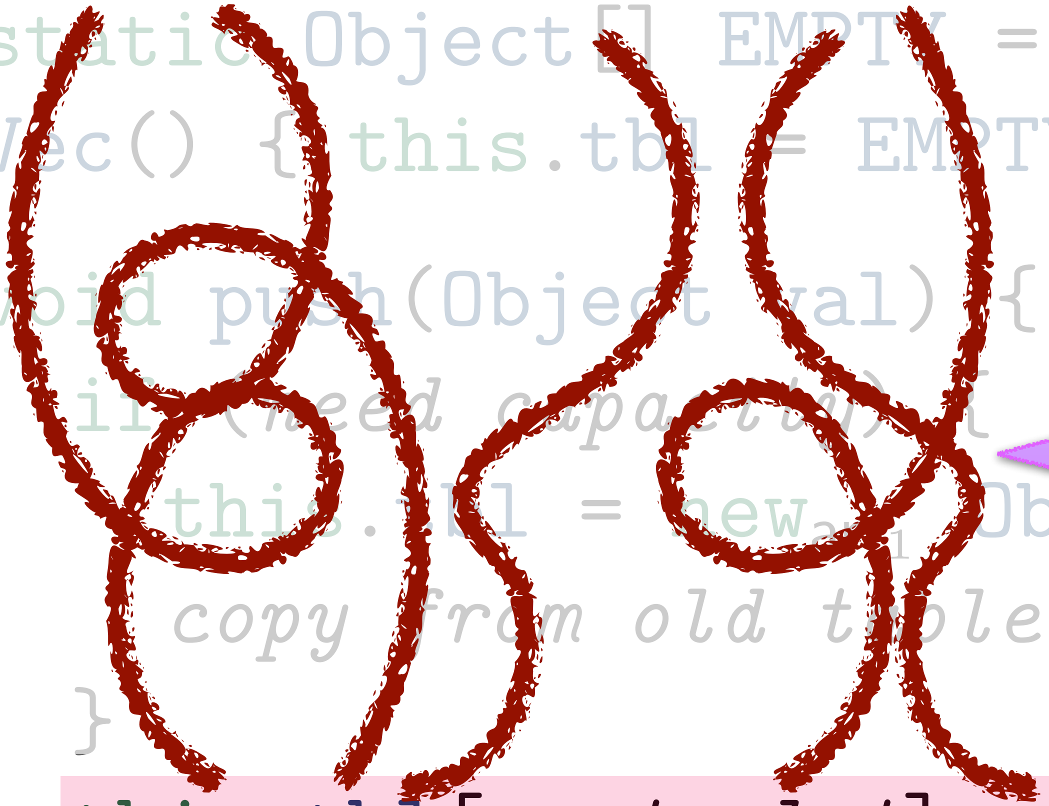
```
class Vec {
  static Object[] EMPTY = new_arr0 Object[1]; ...
  Vec() { this.tbl = EMPTY; capacity initially empty }

  void push(Object val) {
    if (need capacity) {
      this.tbl = new_arr1 Object[more capacity];
      copy from old table
    }
    this.tbl[next slot] = val;
  }
}
```

$arr_0 \cdot [\text{-}] \mapsto act_0 * \mathsf{true}$

A refutation analysis: Try to derive a contradiction with a backwards symbolic analysis

1



```
class Vec {
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  Vec() { this.tbl = EMPTY
  
  void push(Object val) {
    if (need capacity) {
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      copy from old table
    }
    this.tbl[next slot] = val;
  }
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```

Derive a contradiction along all "backwards" path programs

[Beyer, Henzinger, Majumdar, Rybalchenko (2007)]

$$arr_o\cdot[-] \mapsto act_o * \mathsf{true}$$

A refutation analysis: Try to derive a contradiction with a backwards symbolic analysis

1

```
class Vec {
  static Object[] EMPTY = new_arr Object[1]; ...
  Vec() { this.tbl = EMPTY

  void push(Object val) {
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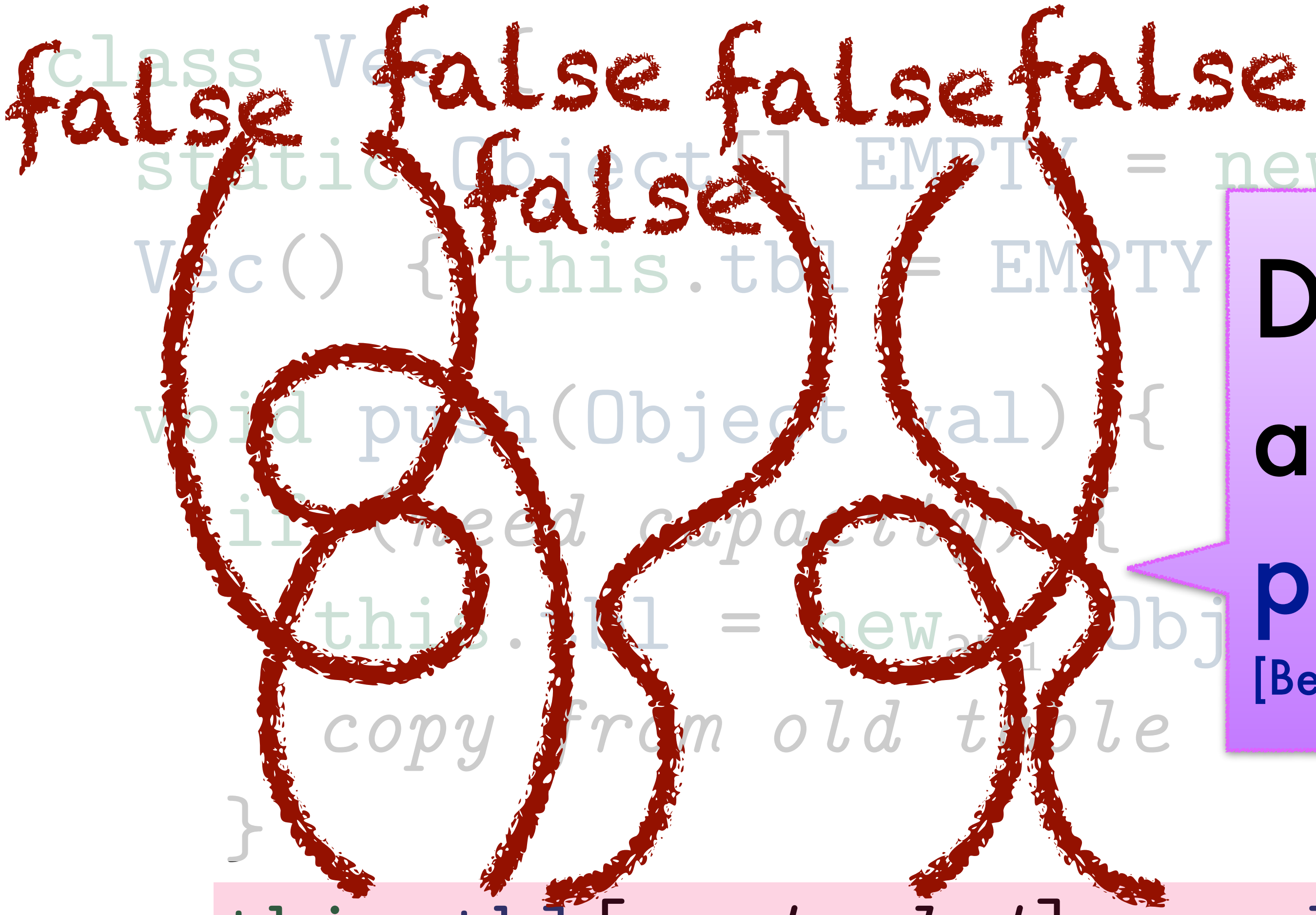
      this.tbl = new_arr Obj
      copy from old table
    }
    this.tbl[next slot] = val;
  }
}
```



Derive a contradiction along all “backwards” path programs

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A refutation analysis: Try to derive a contradiction with a backwards symbolic analysis

1

false false false false

false

```
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Derive a contradiction along all “backwards” path programs

[Beyer, Henzinger, Majumdar, Rybalchenko (2007)]

$arr_0 \cdot [-] \mapsto act_0 * \mathsf{true}$

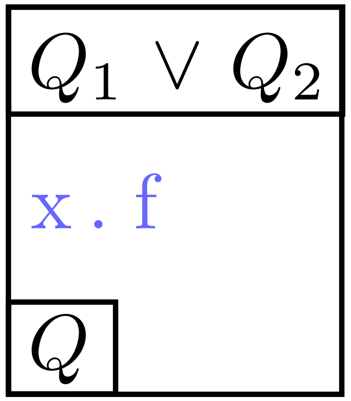
Derive refutations by trying to find witnesses

Roadmap: Precise but with scalability challenges

1

Roadmap: Precise but with scalability challenges

1



$Q_1 \vee Q_2$

x . f

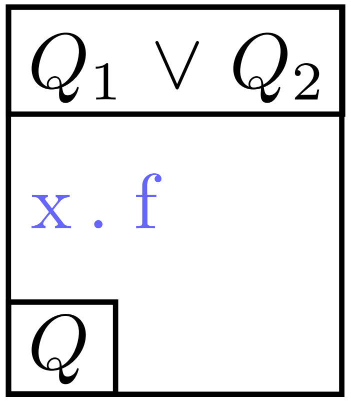
Q

Alias path explosion for strong updates

(On write, case split for each possible alias in Q to maintain separation)

Roadmap: Precise but with scalability challenges

1



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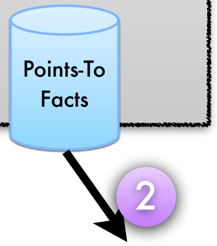

Roadmap: Precise but with scalability challenges

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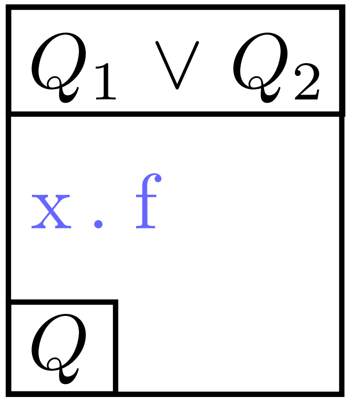

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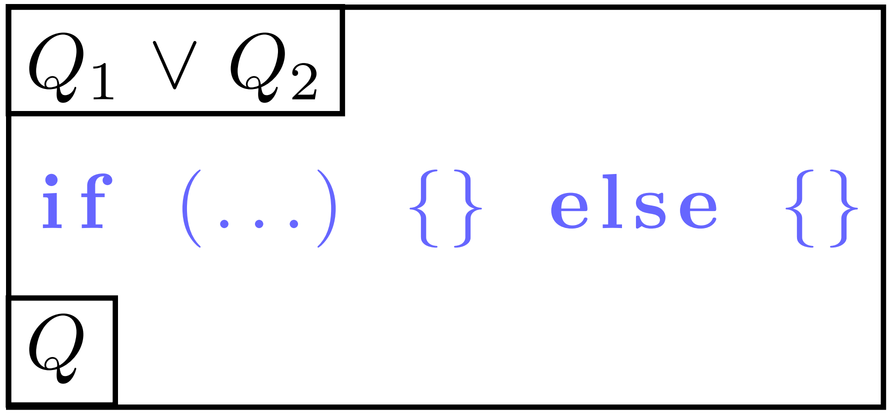
Points-To Facts

2



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if (...) {} else {}

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Control-flow path explosion:

Ignore for now, reasonable if number of guards relevant to Q is small (e.g., [Das et al. (2002)])

Roadmap: Precise but with scalability challenges

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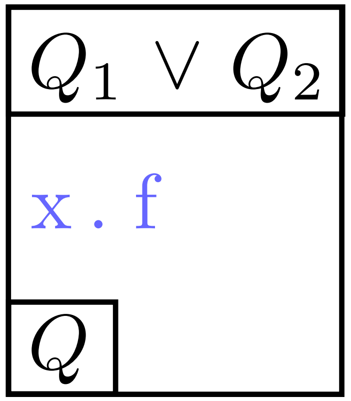

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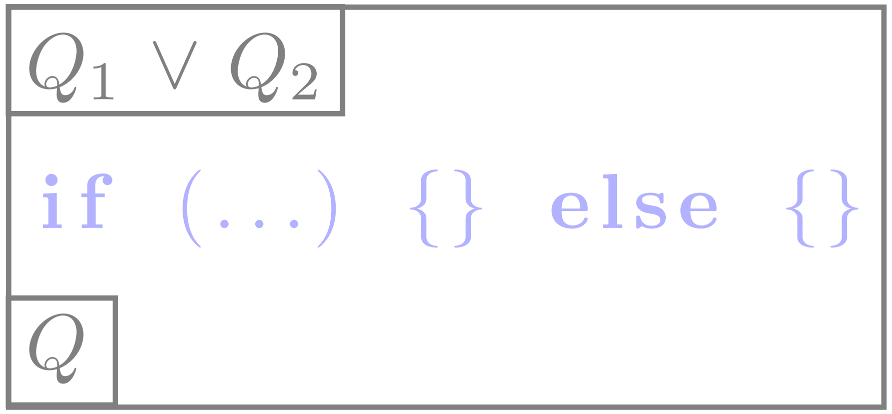

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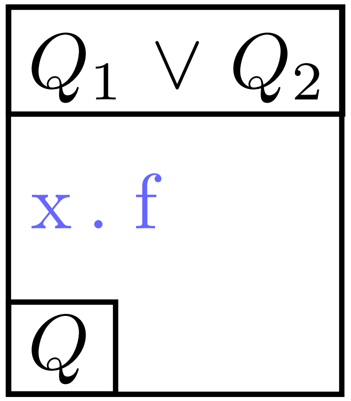

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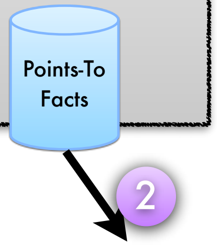

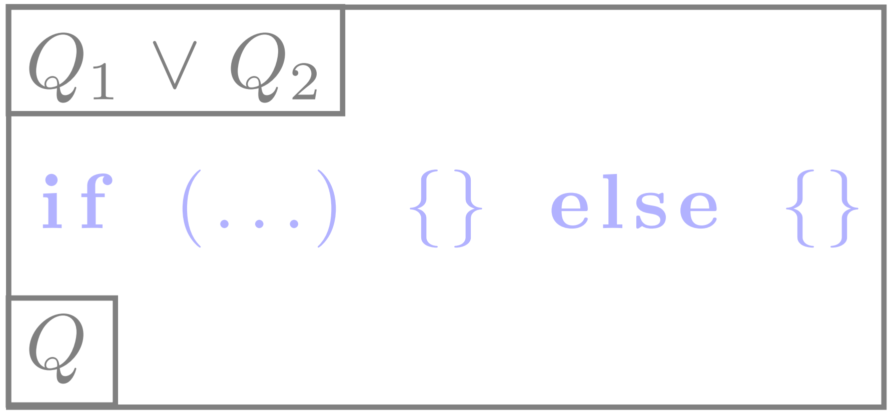

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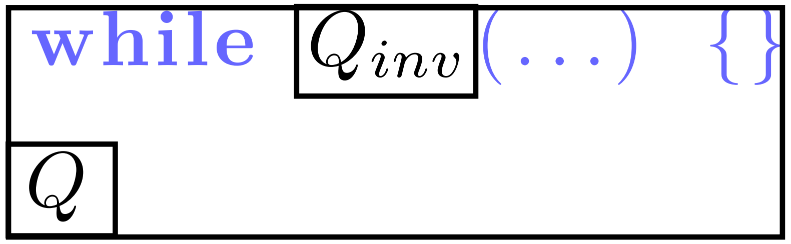
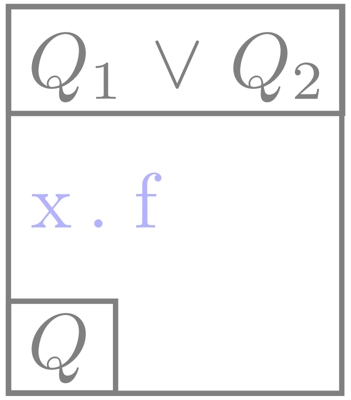


Loops:

Simple loop invariant inference sufficient so far but more sophisticated techniques possible if needed

Roadmap: Precise but with scalability challenges



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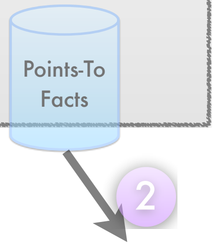

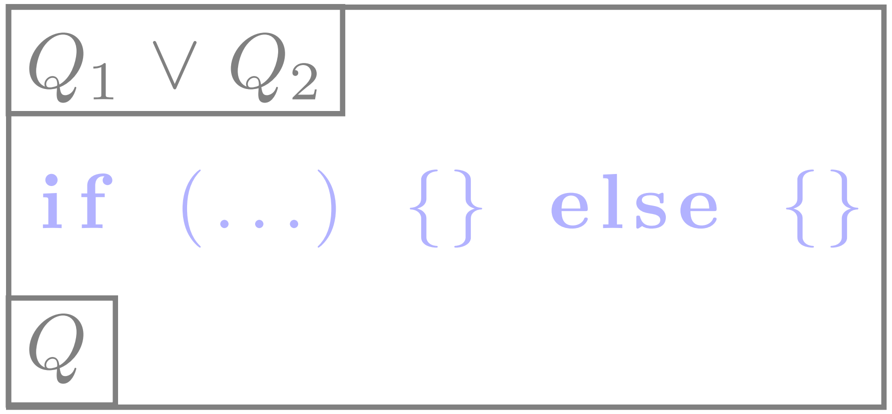

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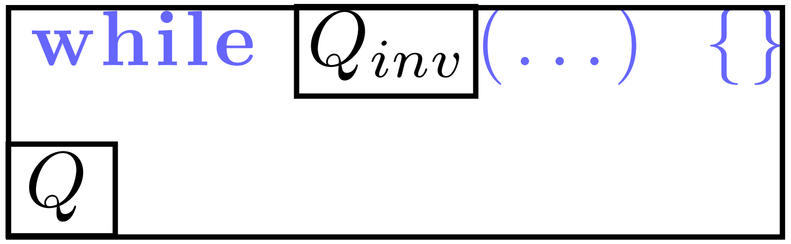

while Q_{inv} (...) {}

Q

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Roadmap: Precise but with scalability challenges

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$Q_1 \lor Q_2$

x.f

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Points-To Facts

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while $\boxed{Q_{inv}}$ (...) {}

Q

Over-approximate what?

Loops:

Simple loop invariant inference sufficient so far but more sophisticated techniques possible if needed

Soundness Criteria

1

Soundness Criteria

1

Concrete Evaluation $\langle \sigma, s \rangle \Downarrow \sigma'$

Soundness Criteria

1

Concrete Evaluation $\langle \sigma, s \rangle \Downarrow \sigma'$ $\quad \sigma \in \mathbf{State} \quad s \in \mathbf{Statement}$

Soundness Criteria

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Abstract Analysis $\vdash \{\widehat{\sigma}\}\ s\ \{\widehat{\sigma}'\}$

Soundness Criteria

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Soundness Criteria

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Standard Total Correctness Soundness Criteria

If $\vdash \{\widehat{\sigma}\}\ s\ \{\widehat{\sigma}'\}$ such that $\sigma \in \gamma(\widehat{\sigma})$,
then $\langle \sigma, s \rangle \Downarrow \sigma'$ for some $\sigma' \in \gamma(\widehat{\sigma}')$.

Soundness Criteria

1

Concrete Evaluation	$\langle \sigma, s \rangle \Downarrow \sigma'$	$\sigma \in \mathbf{State}$ $\quad s \in \mathbf{Statement}$
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If $\vdash \{\widehat{\sigma}\}\ s\ \{\widehat{\sigma}'\}$ **such that** $\sigma' \in \gamma(\widehat{\sigma}')$**,**
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Post: Goal

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"Total" Witness Soundness Criteria

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$\widehat{\sigma} = \bot$?

Soundness Criteria

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Ball, Kupferman, and Yorsh (2005)

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Ball, Kupferman, and Yorsh (2005)

Snugglebug, Alter, DART, ... are under-approximate

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Abstract Analysis $\vdash \{\widehat{\sigma}\}\ s\ \{\widehat{\sigma}'\}$ $\widehat{\sigma} \in \hat{\mathbf{State}}$ $\gamma : \hat{\mathbf{State}} \to \wp(\mathbf{State})$

If $\vdash \{\widehat{\sigma}\}\ s\ \{\widehat{\sigma}'\}$ such that $\sigma' \in \gamma(\widehat{\sigma}')$ and $\langle \sigma, s \rangle \Downarrow \sigma'$, then $\sigma \in \gamma(\widehat{\sigma})$.

Soundness Criteria

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Refutation Soundness Criteria

If $\vdash \{\widehat{\sigma}\}\ s\ \{\widehat{\sigma}'\}$ **such that** $\sigma' \in \gamma(\widehat{\sigma}')$ **and** $\langle \sigma, s \rangle \Downarrow \sigma'$**,** **then** $\sigma \in \gamma(\widehat{\sigma})$**.**

Soundness Criteria

1

If a loop may "produce" a conjunct of the query, we can "assume it does" (weaken the query) only at the cost of precision.

Refutation Soundness Criteria

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Refutations: Prove alarms false with "partial" witnesses, an "easier condition" for loops

Soundness Criteria

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If such that and $\langle \sigma, s \rangle \Downarrow \sigma'$,
then .

Soundness Criteria

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Concrete Evaluation	$\langle \sigma, s \rangle \Downarrow \sigma'$	$\sigma \in \mathbf{State}$ $\quad s \in \mathbf{Statement}$
Abstract Analysis	$\vdash \{\widehat{\sigma}\}\ s\ \{\widehat{\sigma}'\}$	$\widehat{\sigma} \in \mathbf{St\hat{a}te}$ $\quad \gamma : \mathbf{St\hat{a}te} \to \wp(\mathbf{State})$

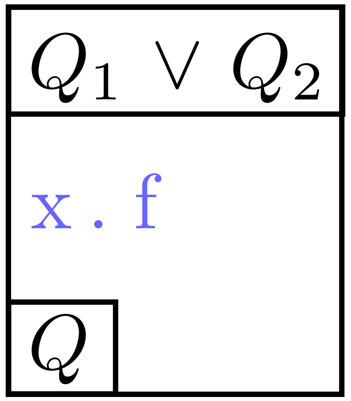
Necessary Precondition Soundness Criteria

If $\vdash \{\widehat{\sigma}\}\ s$ fault **such that** $\sigma \notin \gamma(\widehat{\sigma})$ **and** $\langle \sigma, s \rangle \Downarrow \sigma'$**,**
then $\mathrm{error}(\sigma')$.

Cousot, Cousot, Fähndrich, Logozzo (VMCAI'13)

Roadmap: Precise but with scalability challenges

1



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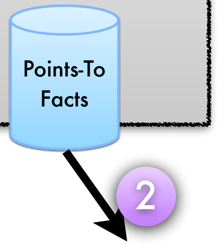

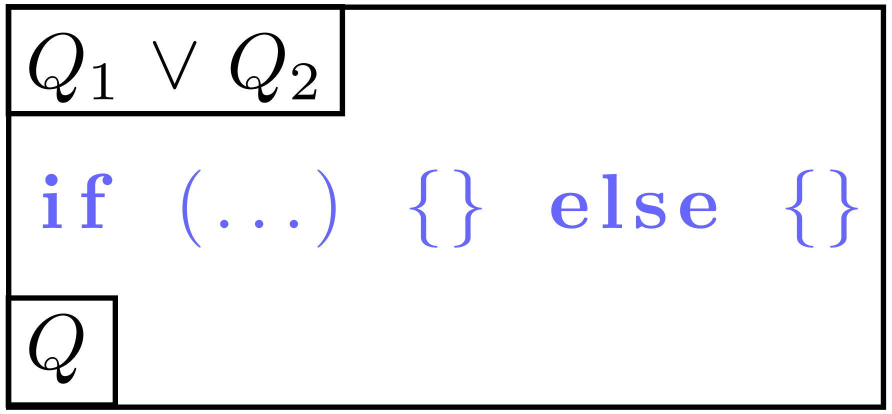

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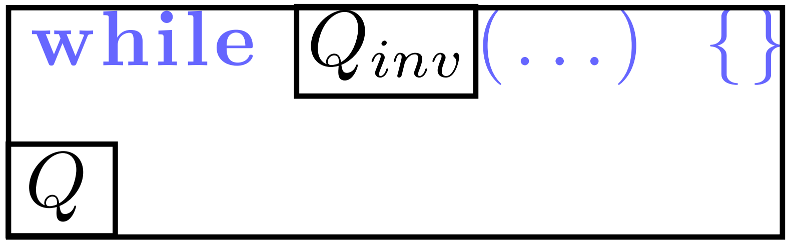

while Q_{inv} (...) {}

Q

Loops:

Simple loop invariant inference sufficient so far but more sophisticated techniques possible if needed

Roadmap: Precise but with scalability challenges

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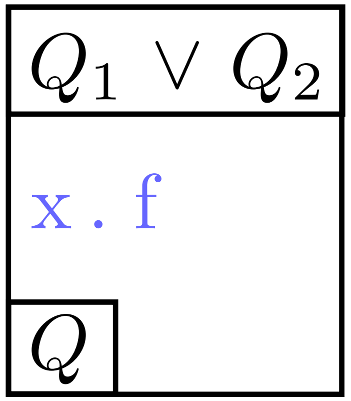

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`x.f`

Q

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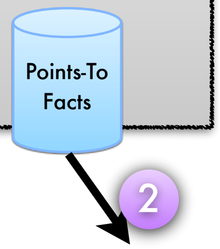

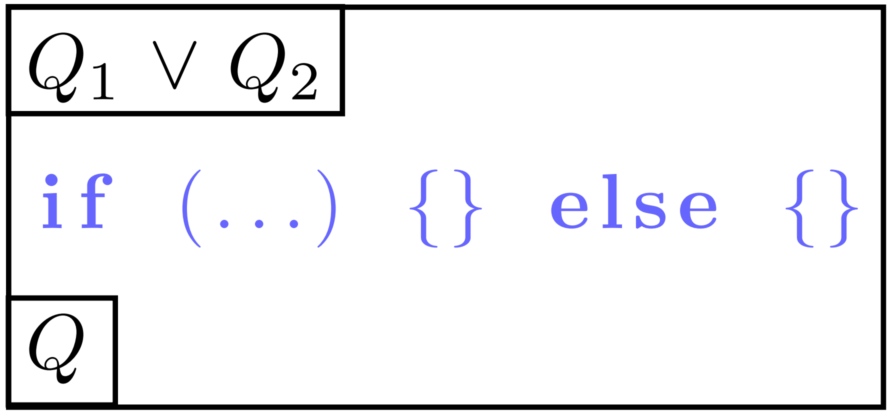

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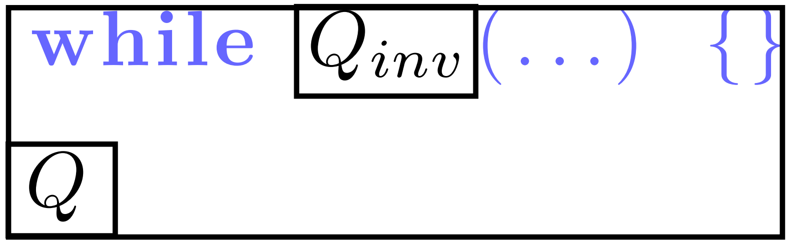

`while` Q_{inv} `(...) {}`

Q

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Roadmap: Precise but with scalability challenges

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$Q_1 \vee Q_2$

```
x.f
```

Q

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(On write, case split for each possible alias in Q to maintain separation)

Points-To Facts

2

$Q_1 \vee Q_2$

```
if (...) {} else {}
```

Q

Control-flow path explosion:

Ignore for now, reasonable if number of guards relevant to Q is small (e.g., [Das et al. (2002)])

```
while
```

Q_{inv}

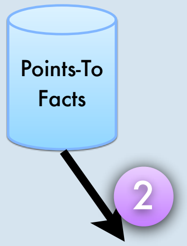
```
(...) {}
```

Q

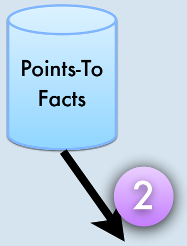
Loops:

Simple loop invariant inference sufficient so far but more sophisticated techniques possible if needed

from constraints: Reducing separation constraints with points-to facts



from constraints: Reducing separation constraints with points-to facts



o from { ..., $\boxed{a_i}$,... }

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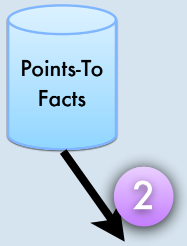

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symbolic object instance (an address)

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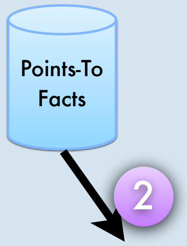

o from { ..., $\boxed{a_i}$,... }

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from constraints: Reducing separation constraints with points-to facts

Points-To Facts

2

o from { ..., $\boxed{a_i}$,... }

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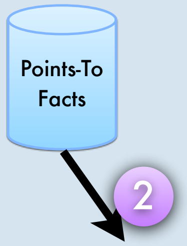
Refute (derive false) if:

from constraints: Reducing separation constraints with points-to facts



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abstract loc in points-to (set of addresses)

Refute (derive false) if:

`i > j ∧ i < j`

from constraints: Reducing separation constraints with points-to facts

Points-To Facts

2

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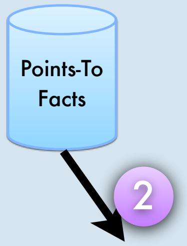
abstract loc in points-to (set of addresses)

Refute (derive false) if:

$i > j \land i < j$

or $o \cdot f \mapsto p \ast o \cdot f \mapsto q \land p \neq q$

from constraints: Reducing separation constraints with points-to facts



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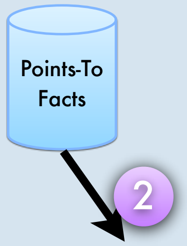
- `i > j ∧ i < j`
- **or** `o·f↦p * o·f↦q ∧ p≠q`
- **or** `o from ∅`

from constraints: Reducing separation constraints with points-to facts



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$\mathtt{i} > \mathtt{j} \wedge \mathtt{i} < \mathtt{j}$

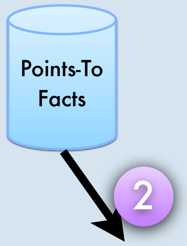
or $\mathtt{o} \cdot \mathtt{f} \mapsto \mathtt{p} * \mathtt{o} \cdot \mathtt{f} \mapsto \mathtt{q} \wedge \mathtt{p} \neq \mathtt{q}$

or $\mathtt{o}$ from $\varnothing$

```
x.f = p
```

$\boxed{\mathtt{y} \cdot \mathtt{f} \mapsto \mathtt{p}}$

from constraints: Reducing separation constraints with points-to facts



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$$\boxed{\mathrm{y} \text{ from } \mathrm{pt}(\mathrm{x}) \cap \mathrm{pt}(\mathrm{y}) \wedge \mathrm{x} = \mathrm{y}}$$

$$\vee \boxed{\mathrm{y} \cdot \mathrm{f} \mapsto \mathrm{p} \wedge \mathrm{x} \neq \mathrm{y}}$$

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$$\boxed{\mathrm{y} \cdot \mathrm{f} \mapsto \mathrm{p}}$$

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Generalized disalias check:

$\mathrm{pt}(\mathrm{x}) \cap \mathrm{pt}(\mathrm{y}) = \varnothing$

from constraints: Reducing separation constraints with points-to facts

Points-To Facts

2

o from { …, $\boxed{a_i}$,… }

symbolic object instance (an address)

abstract loc in points-to (set of addresses)

Restriction on possible abstract locations based on flow in the backwards analysis

Refute (derive false) if:

$\mathtt{i > j \land i < j}$

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x.f = p
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$$\boxed{\mathtt{y \cdot f \mapsto p}}$$

Generalized disalias check:

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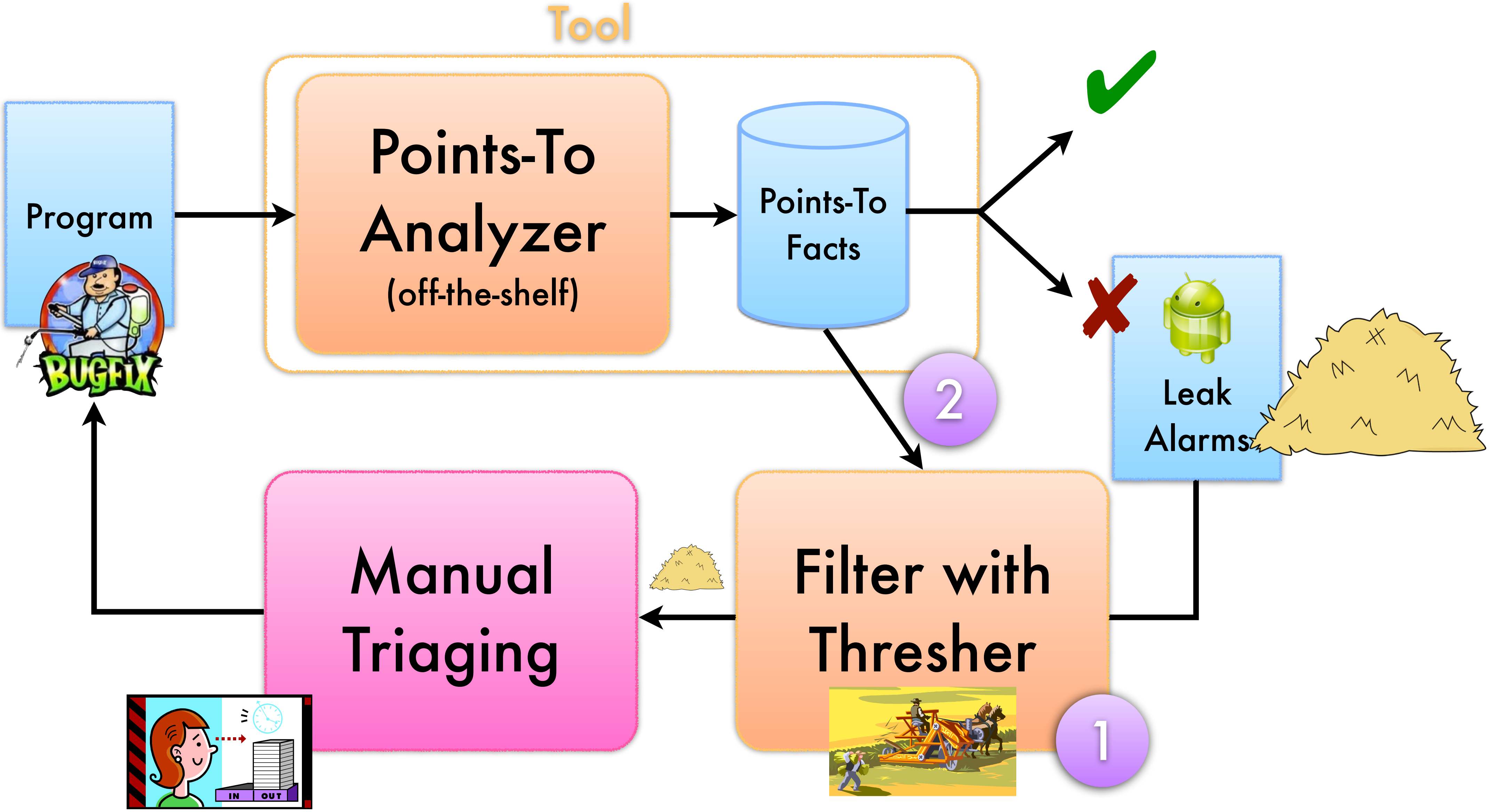
Roadmap: Thresher filters out false alarms by refuting them one-by-one.



Idea 1: Refute points-to on-demand with second precise "filter" analysis

Idea 2: Leverage the facts from the first analysis in the filter analysis to scale

Is Thresher effective at filtering?

1

Thresher analyzes Java VM bytecode

7 Android app benchmarks

2,000 to 40,000 source lines of code

+ 880,000 sources lines of Android framework code

Off-the-shelf, state-of-the-art points-to analysis from WALA

Is Thresher effective at filtering?

1

Program	LOC	Points-To Alarms
PulsePoint	unknown	16
StandupTimer	2K	25
DroidLife	3K	3
SMSPopUp	7K	5
aMetro	20K	54
K9Mail	40K	208
Total	**72K**	**311**

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`staticfield-Activity` pairs

Is Thresher effective at filtering?

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Program	LOC	Points-To Alarms	Thresher Refuted
PulsePoint	unknown	16	8
StandupTimer	2K	25	15
DroidLife	3K	3	0
SMSPopUp	7K	5	1
aMetro	20K	54	18
K9Mail	40K	208	130
Total	**72K**	**311**	**172**

`staticfield-Activity` pairs

Filtered

Is Thresher effective at filtering?

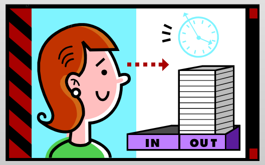
1

Program	LOC	Points-To Alarms	Thresher Refuted	True Bugs
PulsePoint	unknown	16	8	8
StandupTimer	2K	25	15	0
DroidLife	3K	3	0	3
SMSPopUp	7K	5	1	4
aMetro	20K	54	18	36
K9Mail	40K	208	130	64
Total	**72K**	**311**	**172**	**115**

staticfield-Activity pairs

Filtered

Manual



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Program	LOC	Points-To Alarms	Thresher Refuted	True Bugs
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Is Thresher effective at filtering?

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Program	LOC	Points-To Alarms	Thresher Refuted	True Bugs	Thresher Time (s)
PulsePoint	unknown	16	8	8	95
StandupTimer	2K	25	15	0	1068
DroidLife	3K	3	0	3	1
SMSPopUp	7K	5	1	4	46
aMetro	20K	54	18	36	18
K9Mail	40K	208	130	64	374
Total	**72K**	**311**	**172**	**115**	**1602**

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< ~coffee to lunch break

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Is Thresher effective at filtering?

1

Program	LOC	Points-To Alarms	Thresher Refuted	True Bugs	Thresher Time (s)	False Alarm %
PulsePoint	unknown	16	8	8	95	0
StandupTimer	2K	25	15	0	1068	100
DroidLife	3K	3	0	3	1	0
SMSPopUp	7K	5	1	4	46	0
aMetro	20K	54	18	36	18	0
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Total	**72K**	**311**	**172**	**115**	**1602**	**17**

% after filtering

Is Thresher effective at filtering?

1

Program	LOC	Points-To Alarms	Thresher Refuted	True Bugs	Thresher Time (s)	False Alarm %	Filtered %
PulsePoint	unknown	16	8	8	95	0	100
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SMSPopUp	7K	5	1	4	46	0	100
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K9Mail	40K	208	130	64	374	18	90
Total	**72K**	**311**	**172**	**115**	**1602**	**17**	**88**

% after filtering

Is Thresher effective at filtering?

1

Program	LOC	Points-To Alarms	Thresher Refuted	True Bugs	Thresher Time (s)	False Alarm %	Filtered %
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StandupTimer	2K	25	15	0	1068	100	60
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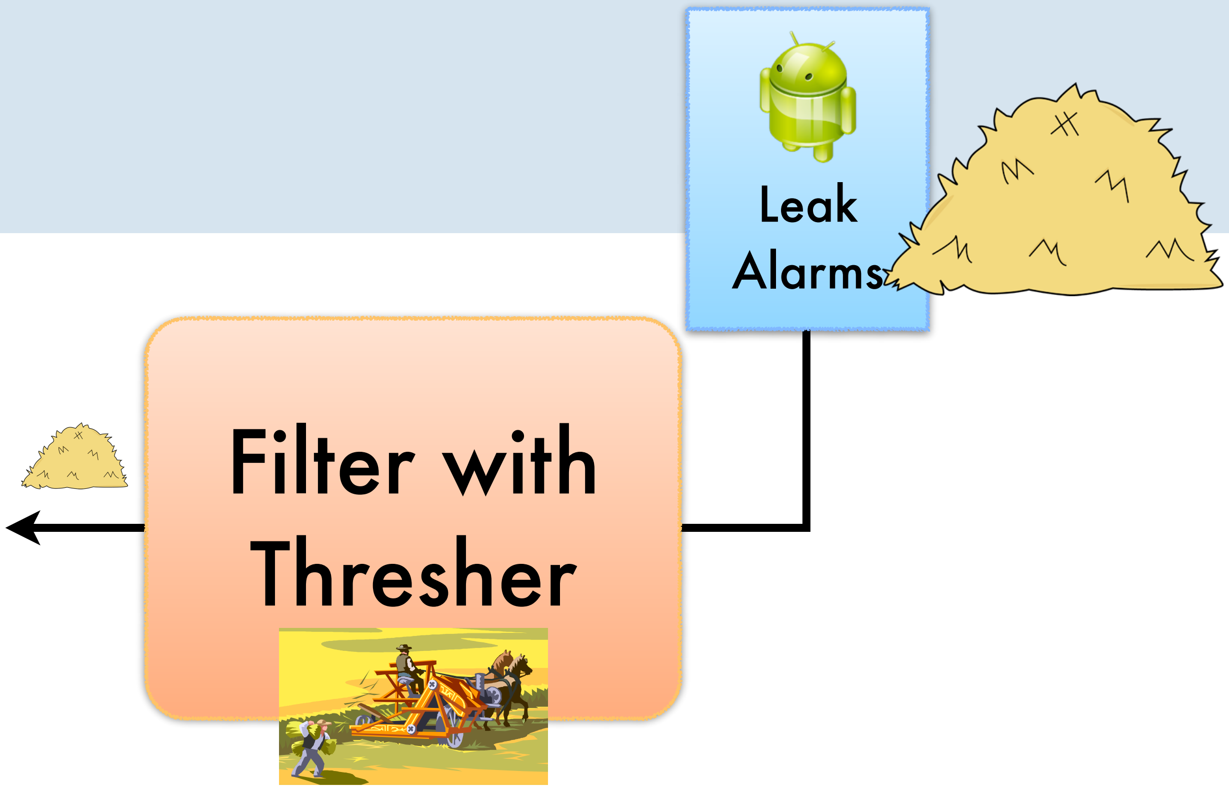
False alarms down to 17% from 63% (points-to analysis only)

Thresher filters 88% of false alarms from points-to analysis

Some Highlights

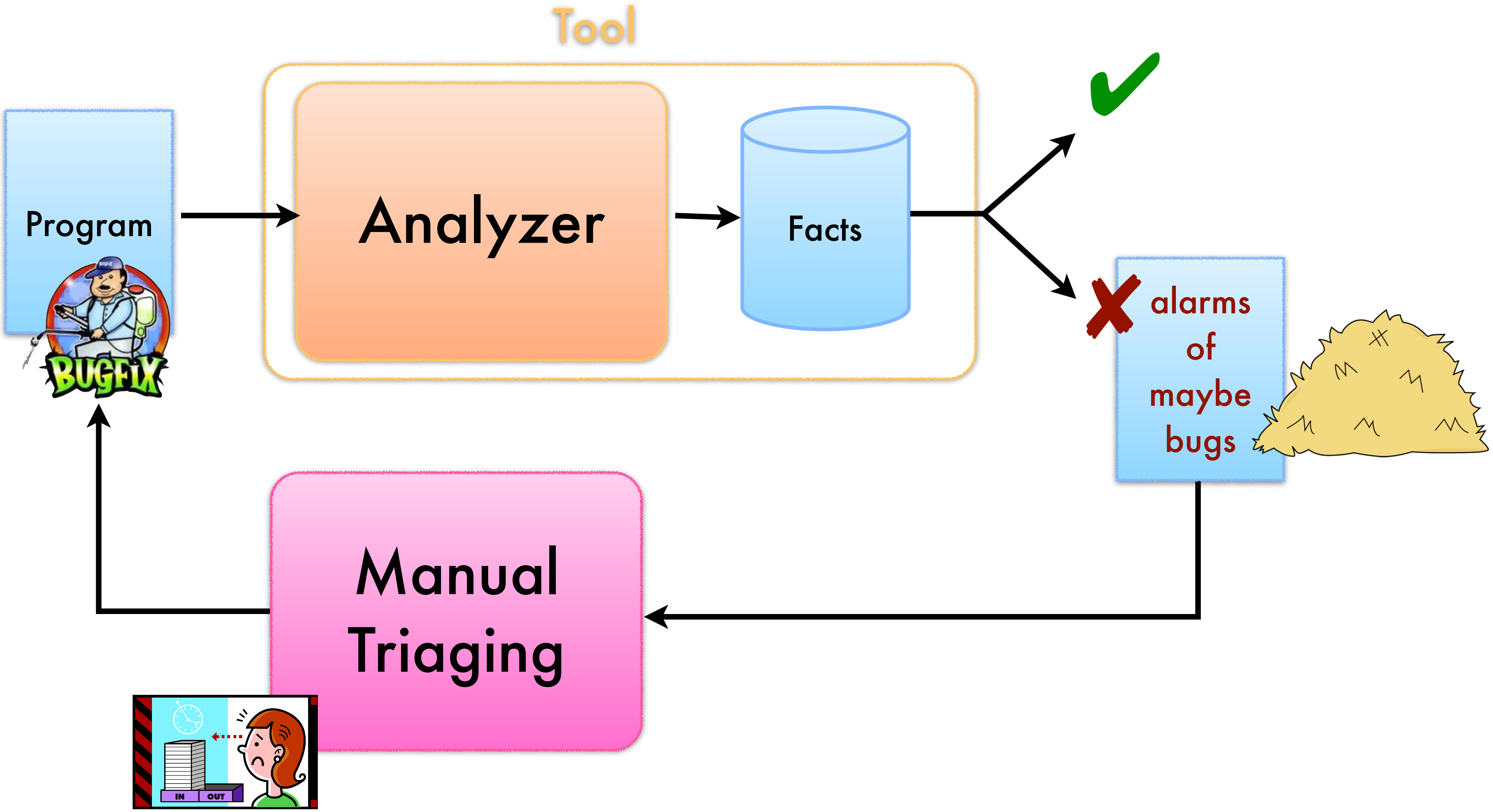


Thresher: Precise Refutations for Heap Reachability

Assist in triage of queries about heap relations

- Assume alarms false, prove them so (refute) automatically with a “partial” witness search
- Reduced separation constraints with points-to facts
- Filters out ~90% of false alarms to expose true bugs
- Application: Find memory leaks and eliminate crashes in Android

Final Commentary: Design and apply analyses to the whole bug mitigation process!



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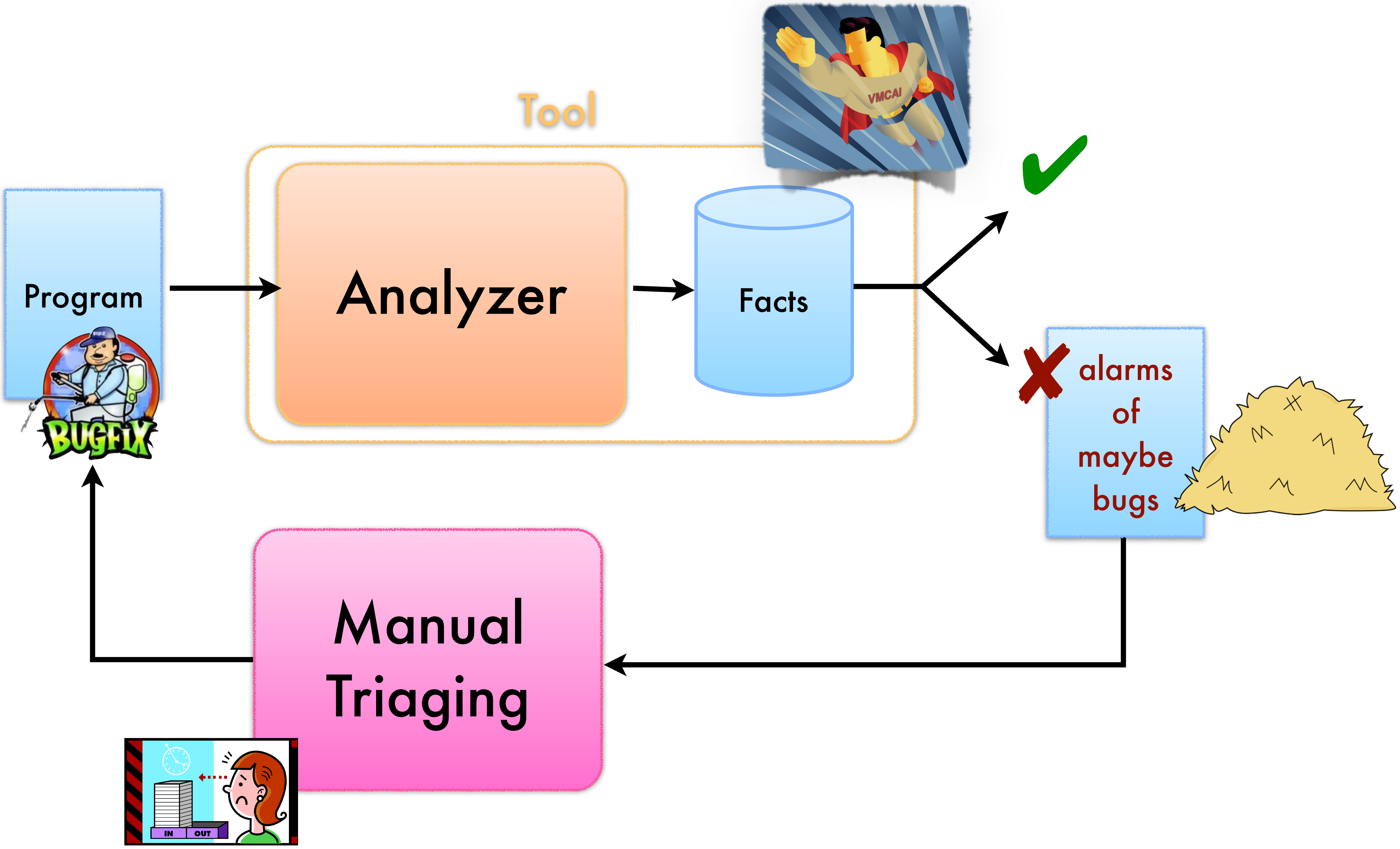

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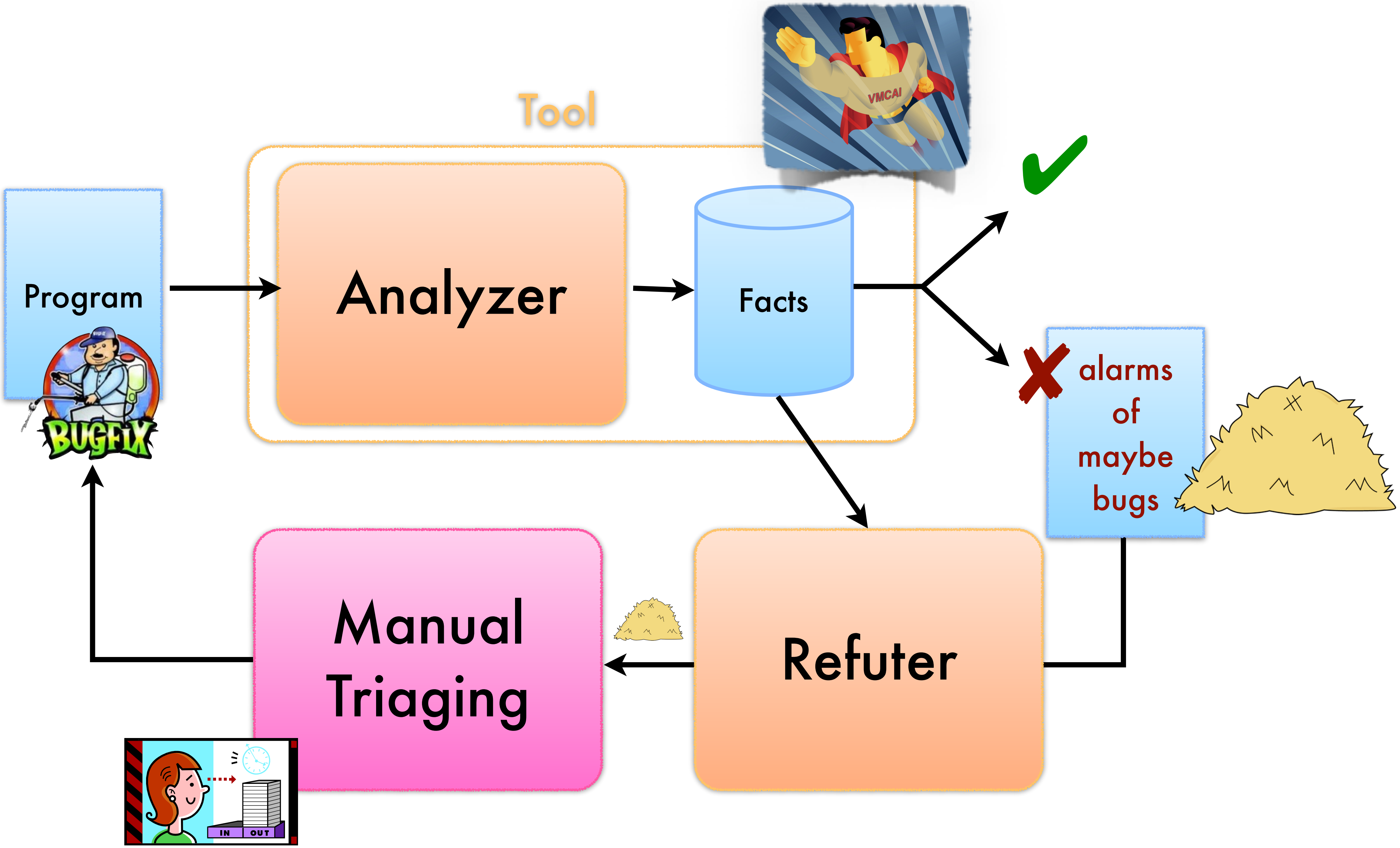

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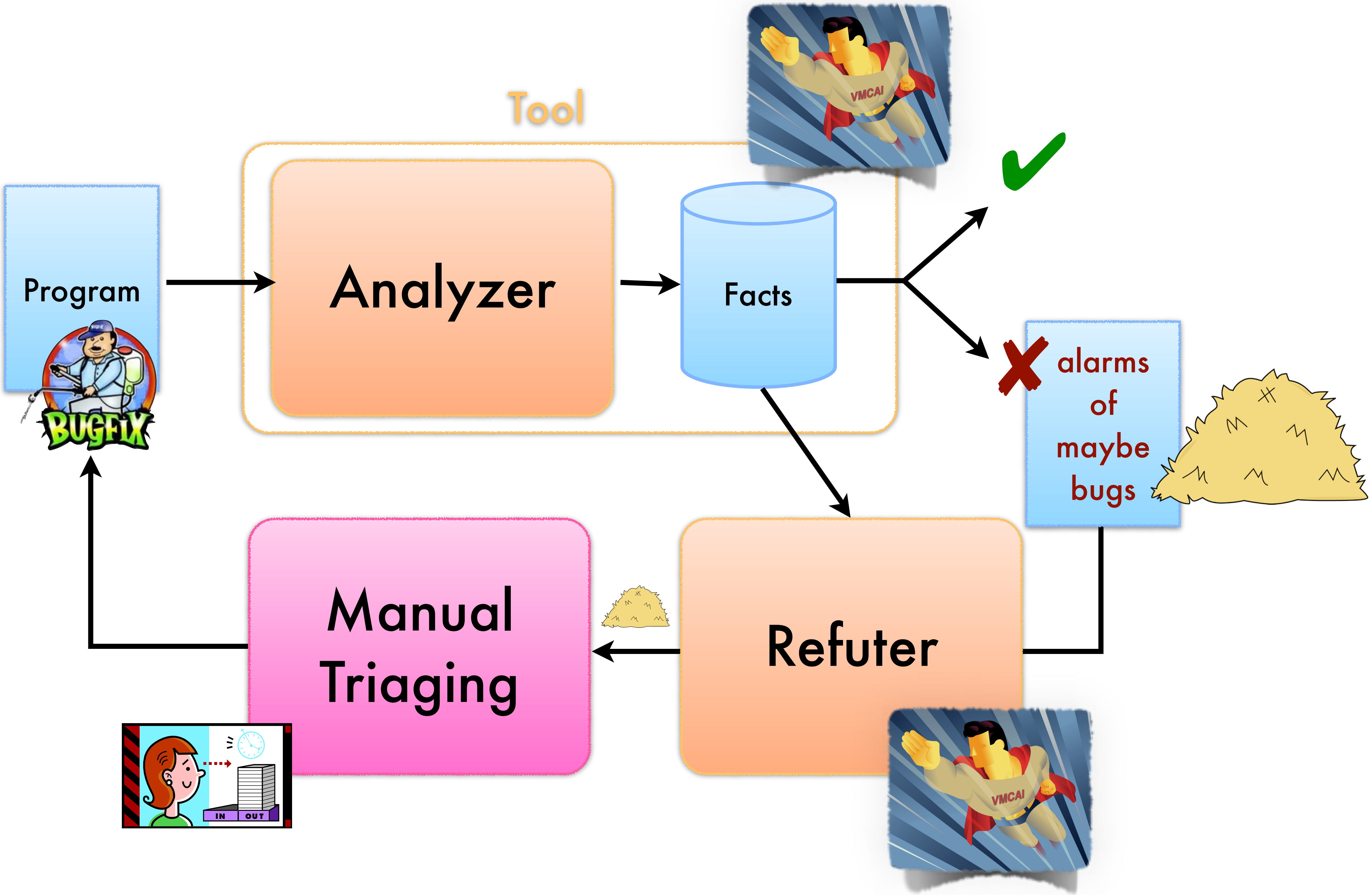

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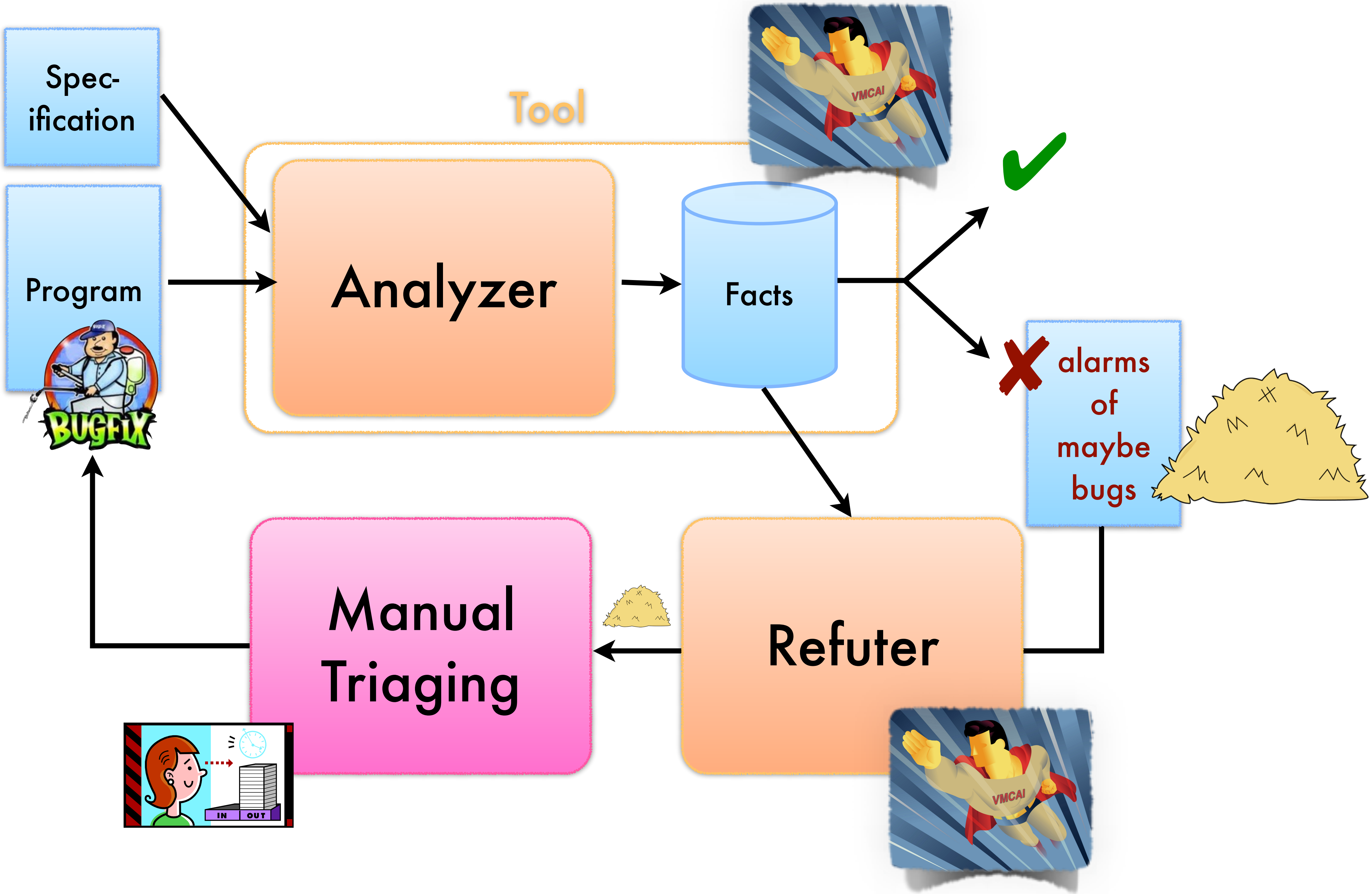


Spec-ification

Program

Tool

Analyzer

Facts

✔

✘ alarms of maybe bugs

Manual Triaging

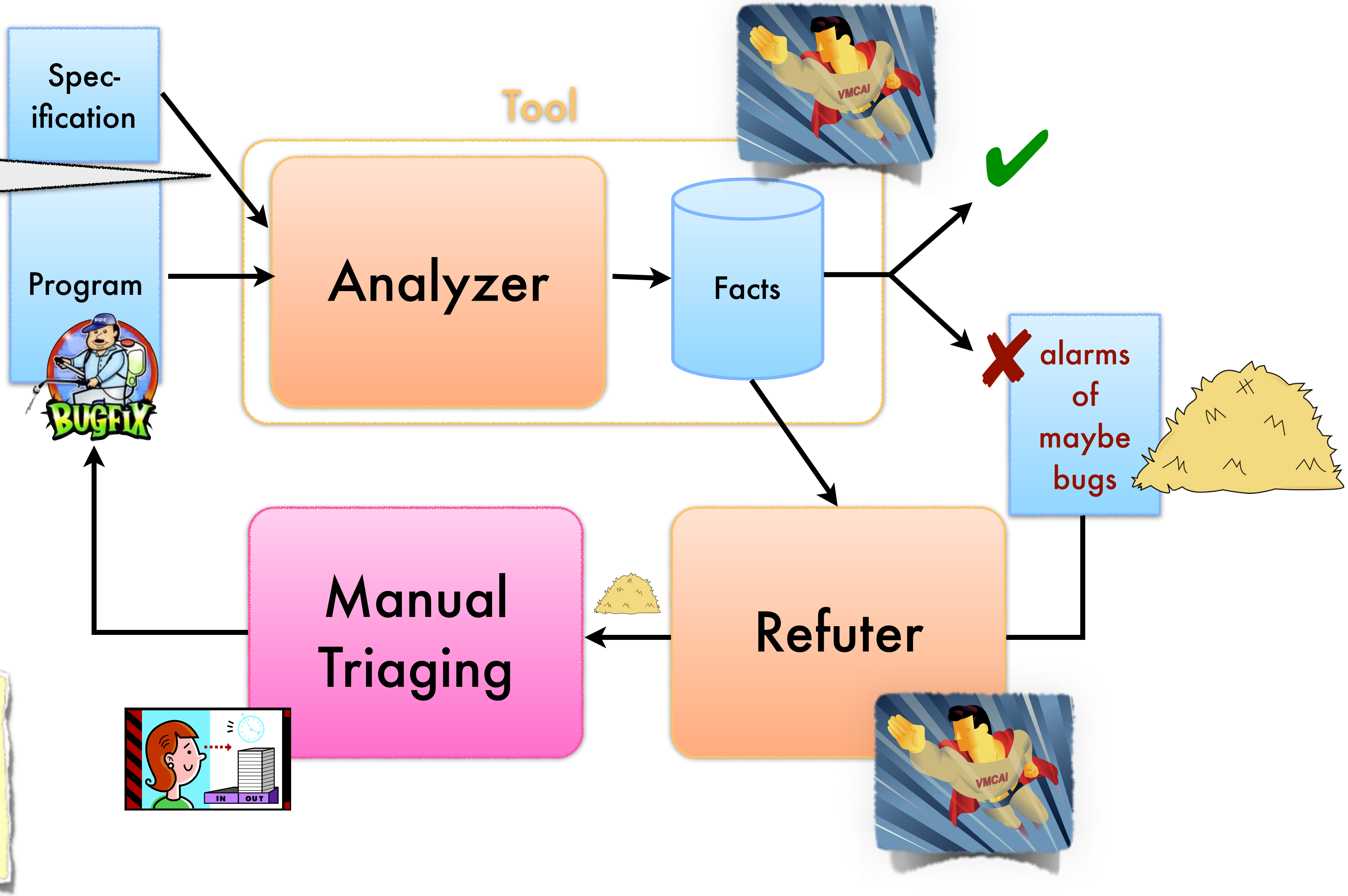
Refuter

Final Commentary: Design and apply analyses to the whole bug mitigation process!

Fissile Types: Checking Almost Everywhere Invariants

[Coughlin+ POPL'14]

Wed
11:45am



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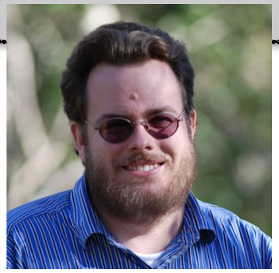
Fissile Types: Checking Almost Everywhere Invariants
[Coughlin+ POPL'14]



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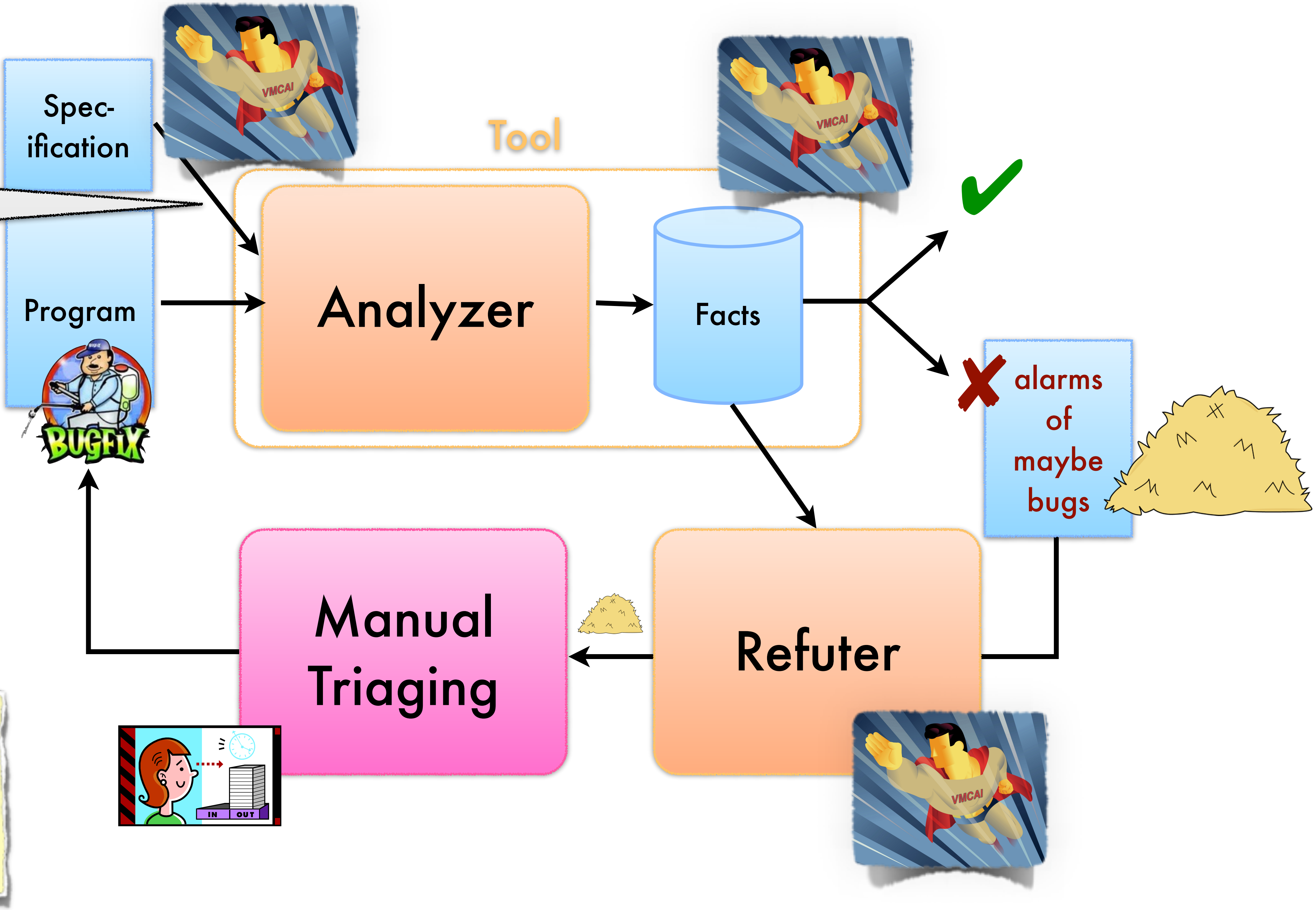

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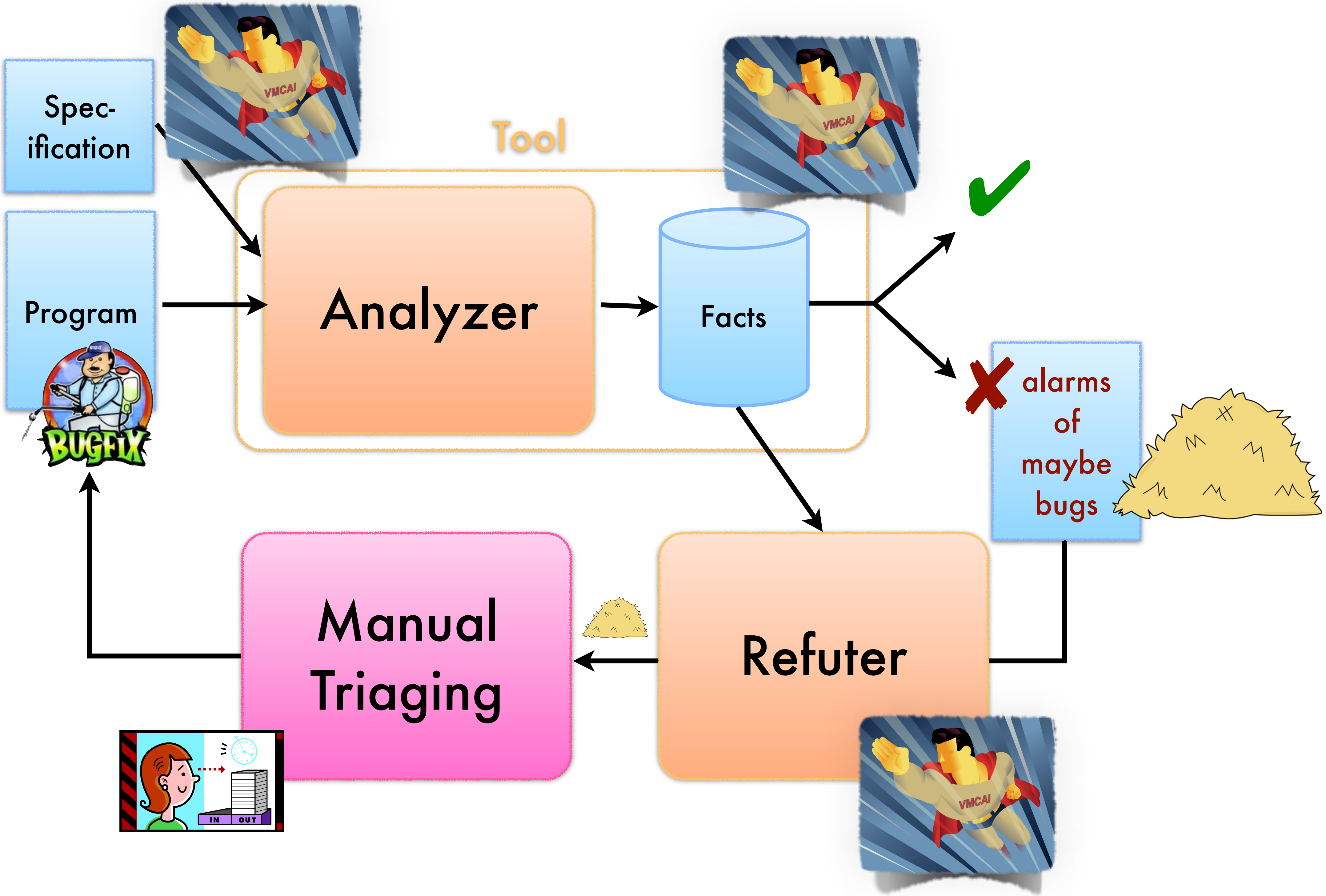

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Thank You!

PLV

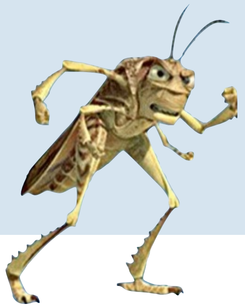
www.cs.colorado.edu/~bec
pl.cs.colorado.edu

Android
OS

Android
OS

... in the process of finding leaks in apps

Find Android's HashMap bug ...



```
class HashMap {
  static Object[] EMPTY = new Object[2]; ...
  HashMap() { this.tbl = EMPTY; capacity initially empty }

  void put(Object key, Object val) {
    if (need capacity) {
      this.tbl = new Object[more capacity];
      copy from old table
    }
    this.tbl[bucket using hash of key] = val;
  }

  HashMap(Map m) {
    if (m.size() < 1) { this.tbl = EMPTY; }
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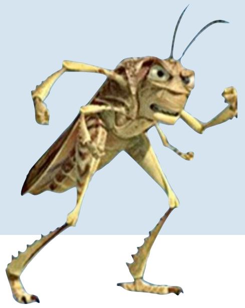

Null object pattern: Should never be written to

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class HashM
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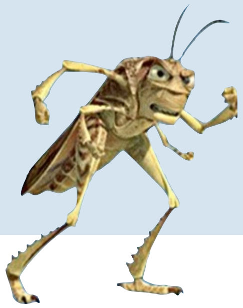

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allocate new backing array on first write

Find Android's HashMap bug ...

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allocate new backing array on first write

An “evil” implementation of the `Map` interface can corrupt `EMPTY`. Then, all `HashMap`s created in the future will be corrupted.

Find Android’s HashMap bug …

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allocate new backing array on first write

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return “evil” content

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Find Android’s HashMap bug …

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  copy from m
 }
}
```

allocate new backing array on first write

We reported this, Google fixed it

https://android-review.googlesource.com/#/c/52183/

return 0

return “evil” content

An “evil” implementation of the Map interface can corrupt EMPTY. Then, all HashMaps created in the future will be corrupted.