Refuting Heap Reachability

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University of Colorado Boulder

July 31, 2014

National Chiao Tung University
國立交通大學

Sam Blackshear
CU Boulder

Manu Sridharan
Samsung

PLV

Lab: **Program analysis** in the **whole** bug mitigation **process**

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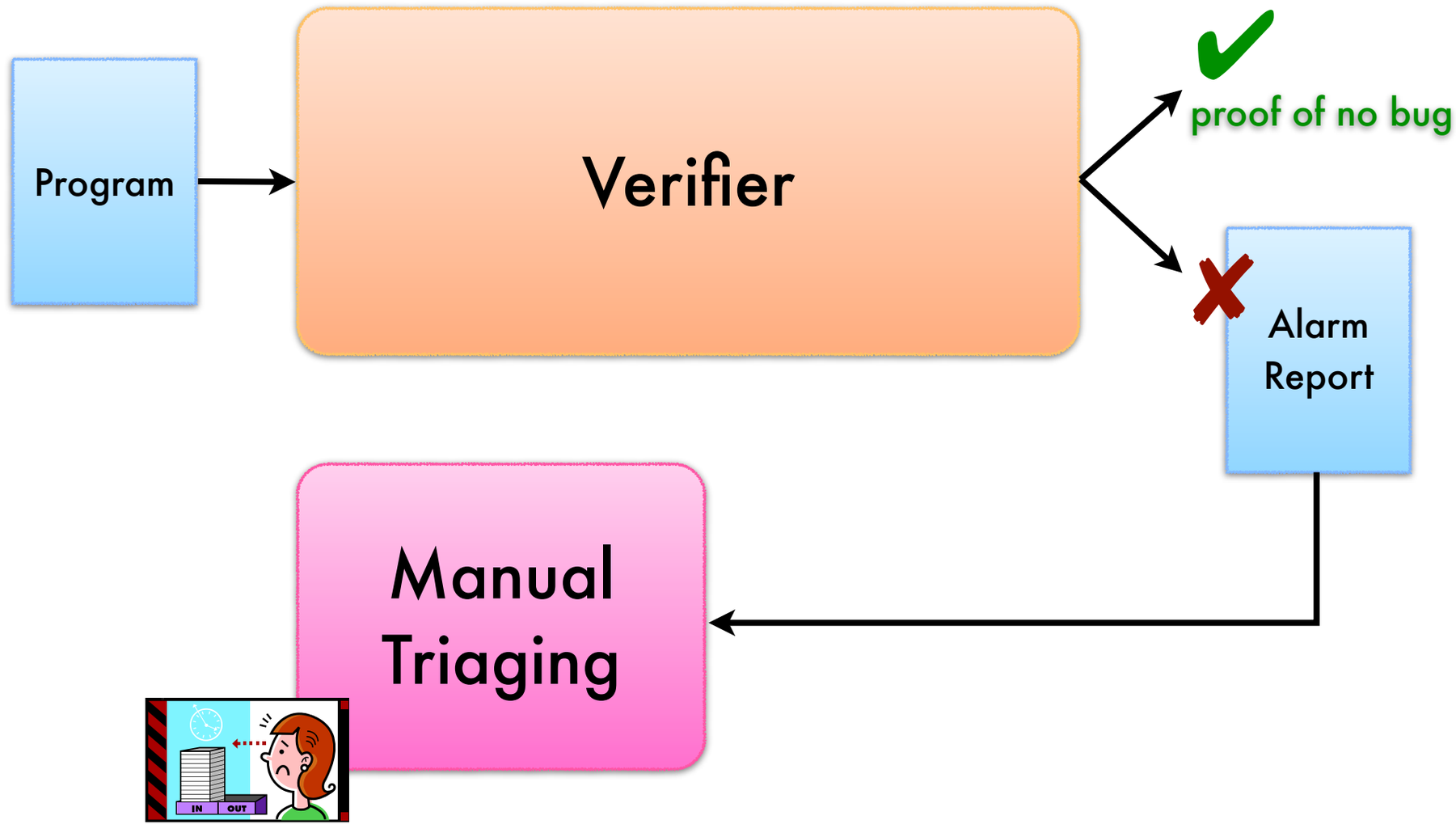

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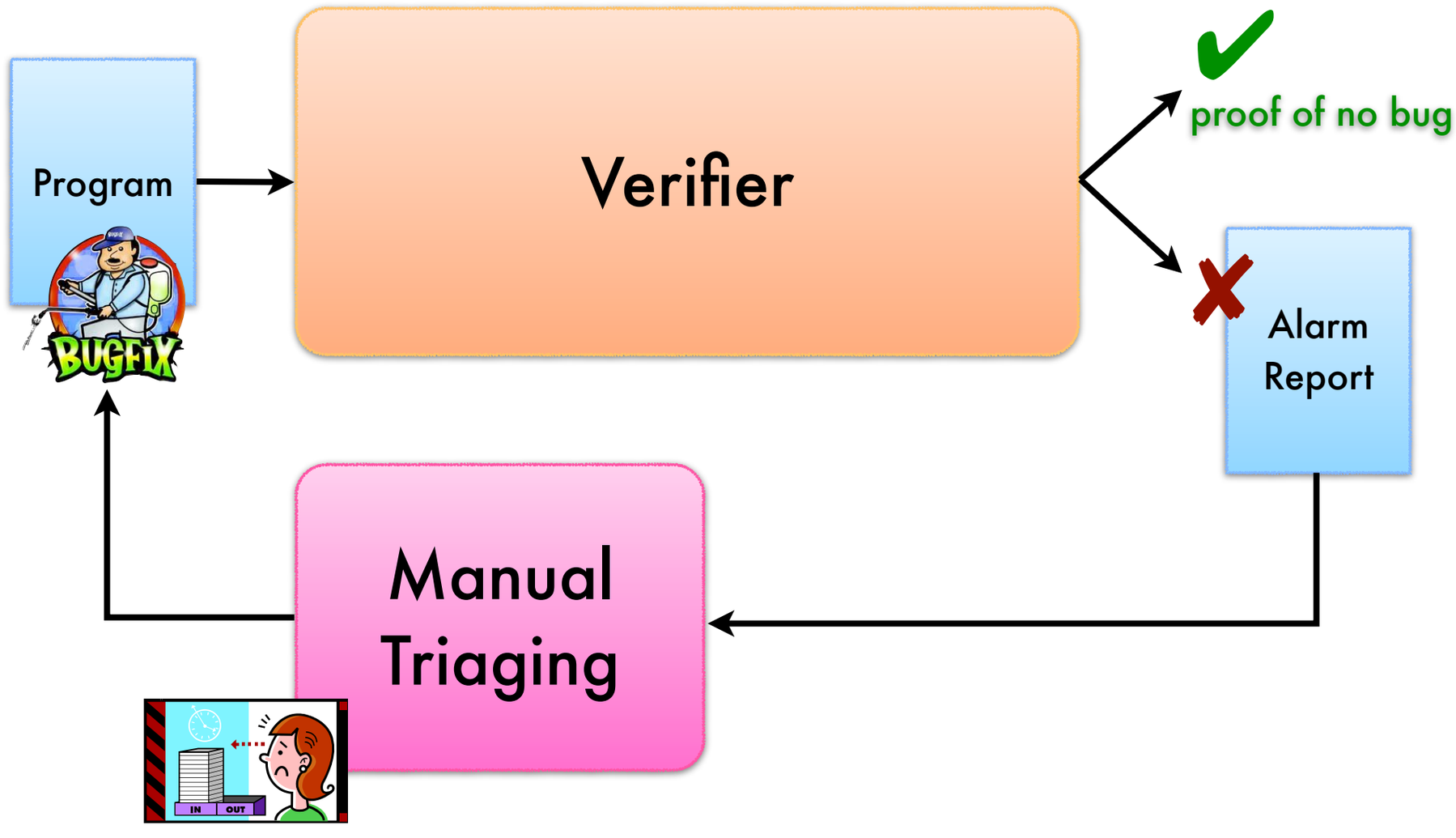

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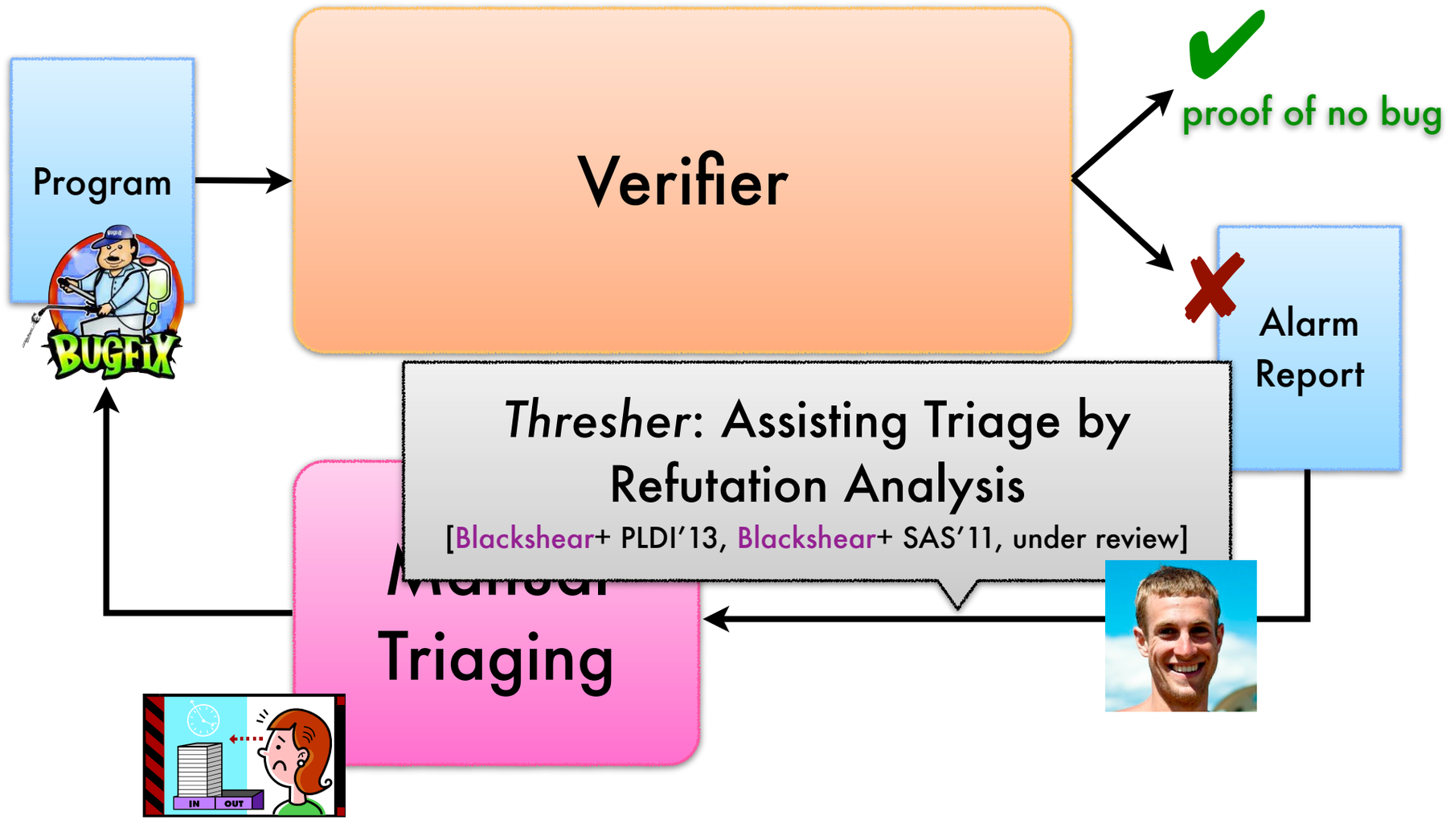

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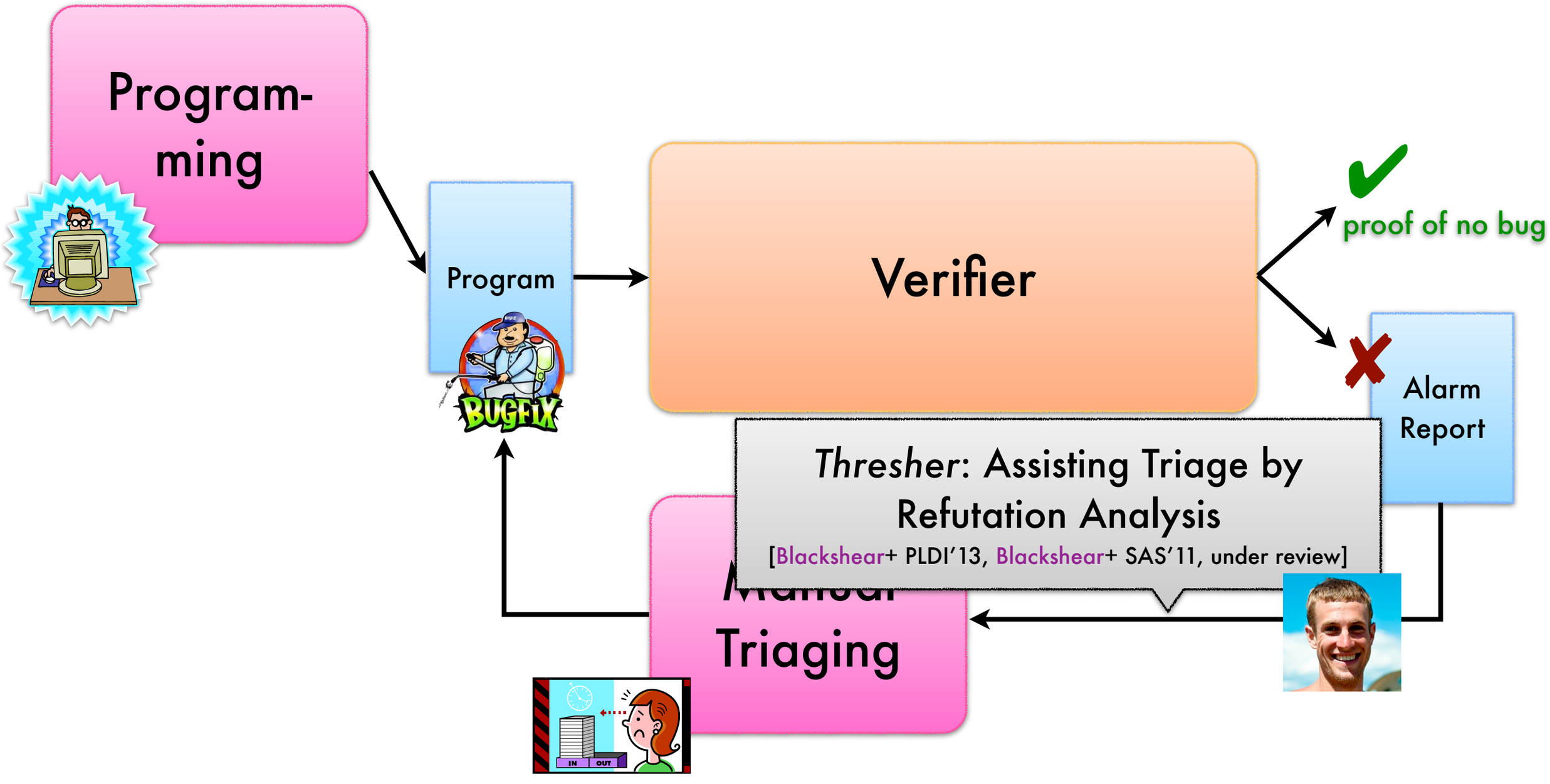

Thresher: Assisting Triage by Refutation Analysis

[Blackshear+ PLDI'13, Blackshear+ SAS'11, under review]

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Enforcement Windows: Measuring Bug Avoidance
[Coughlin+ ISSTA'12]

Program-ming

Program

Verifier

✔ proof of no bug

✘ Alarm Report

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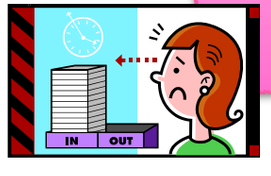
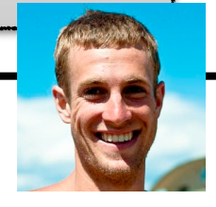
Manual Triaging





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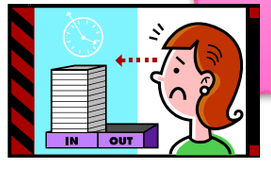

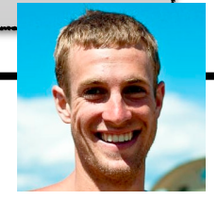

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[Coughlin+ POPL'14, in prep]

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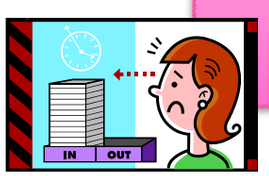

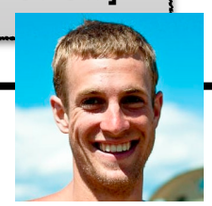

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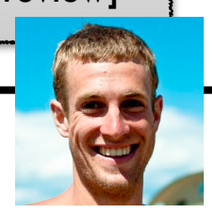

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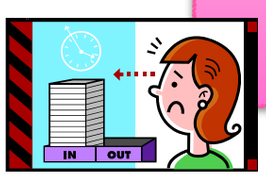

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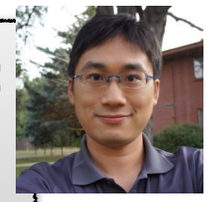
Static Incrementalization of Data Structure Checks
[under review]



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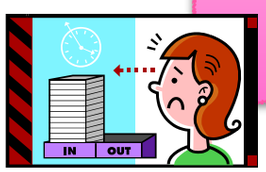

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Jsana: Abstract Domain Combinators for Dynamic Languages
[Cox+ ECOOP'13, Cox+ SAS'14, under review]

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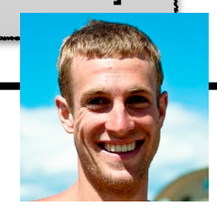

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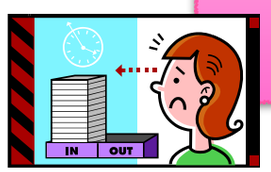

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This Talk

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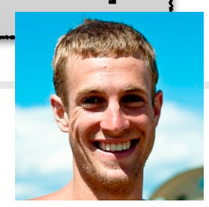

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program heap

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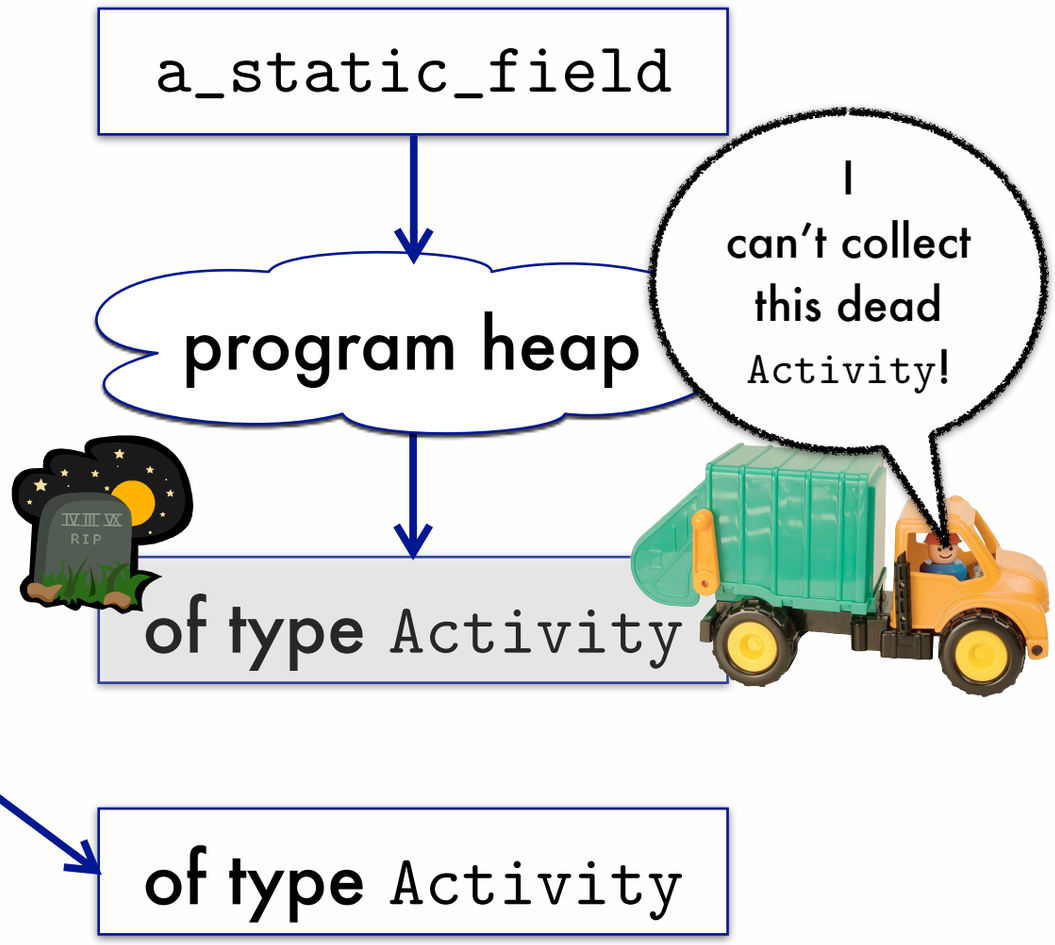

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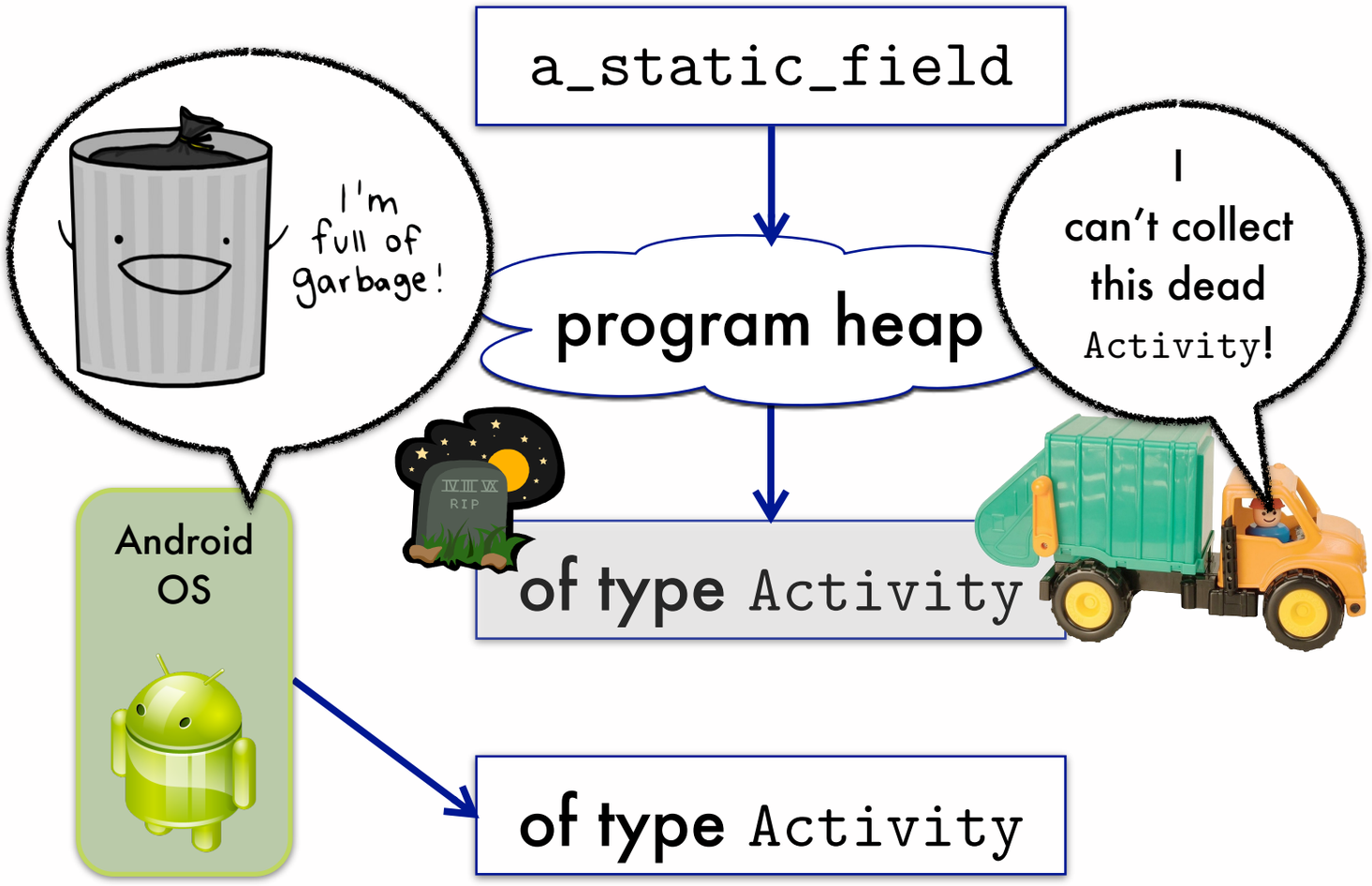

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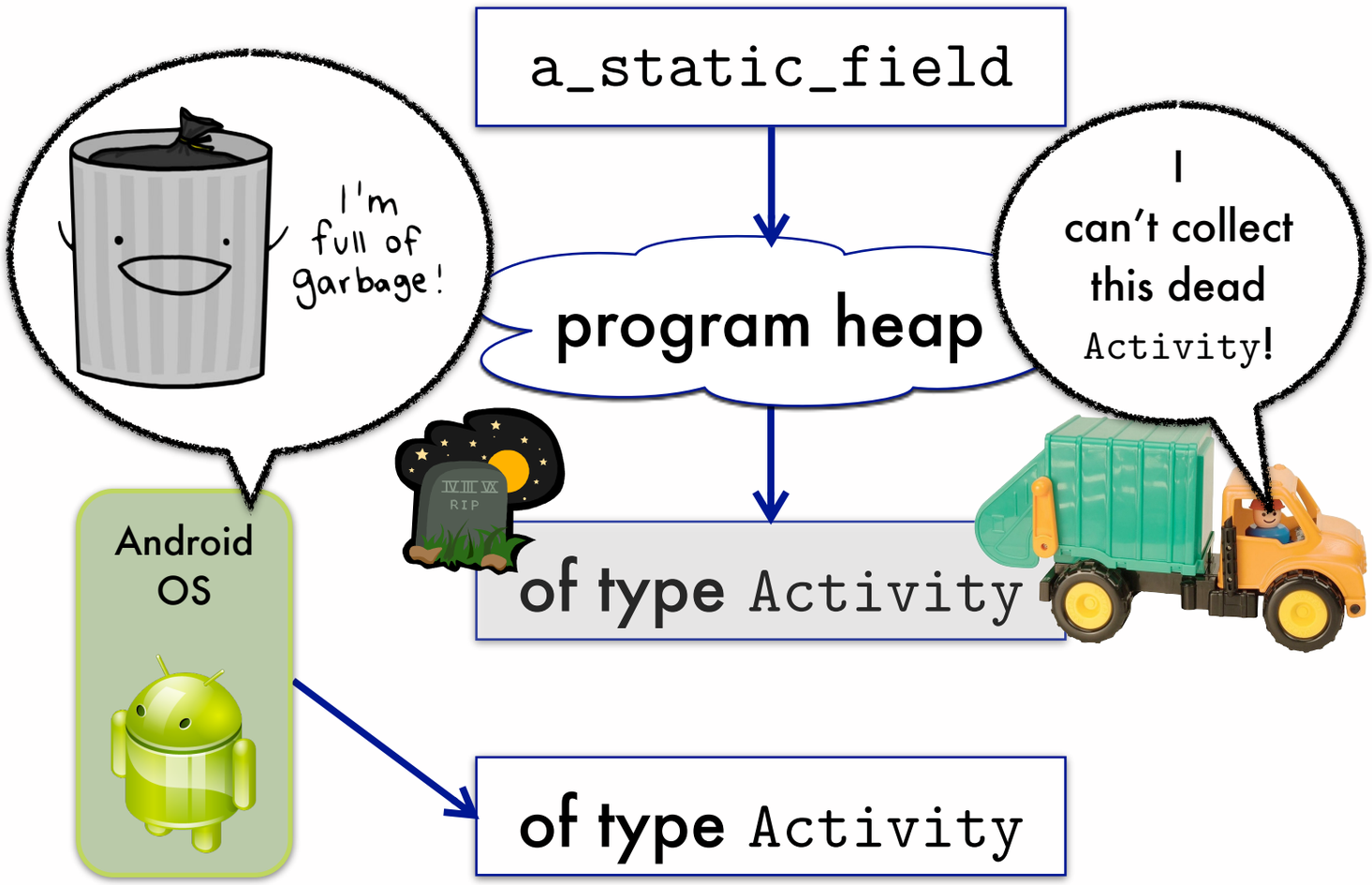

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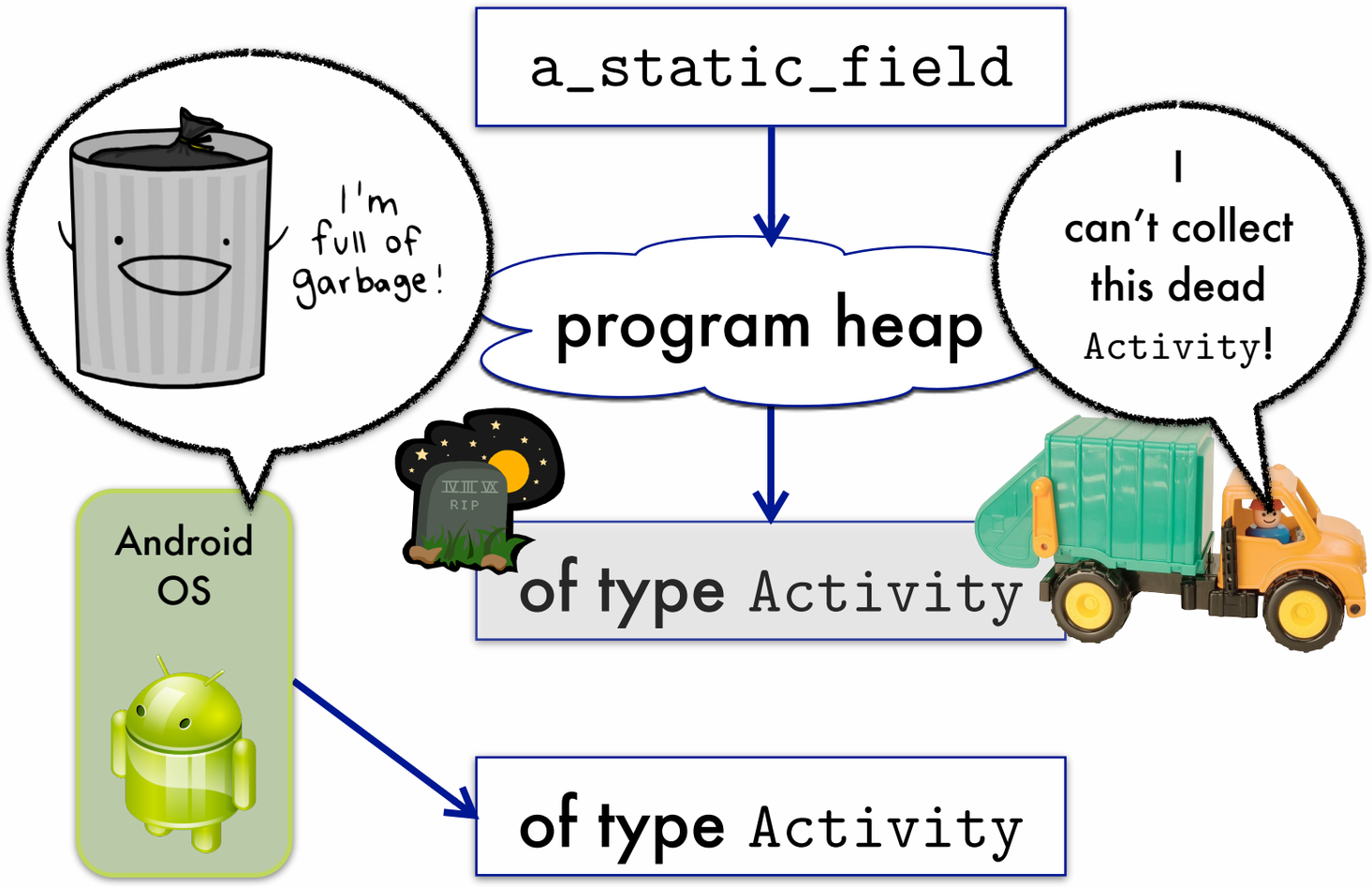

`Activity` objects encapsulate the UI

"an `Activity` leak"

Bug: Holding reference to "old" `Activity`

The expert recommendation ...

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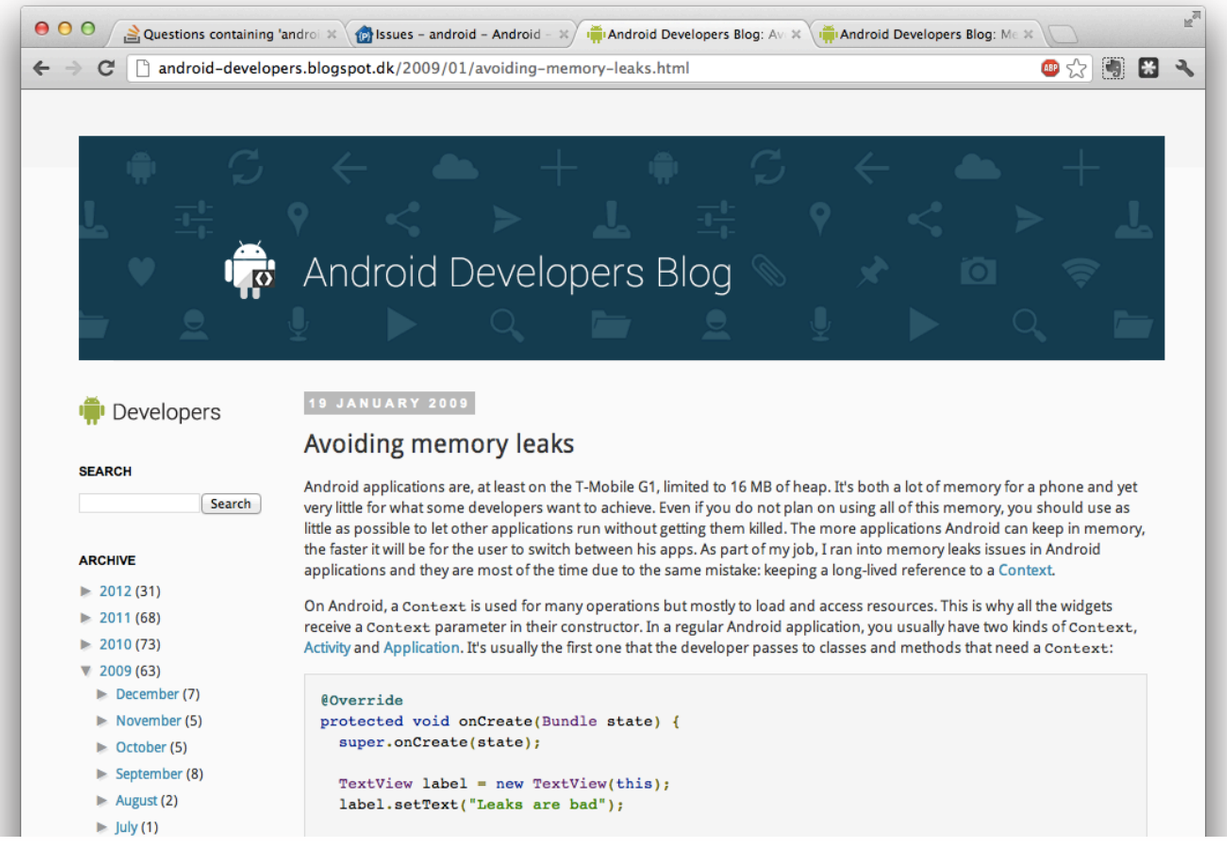
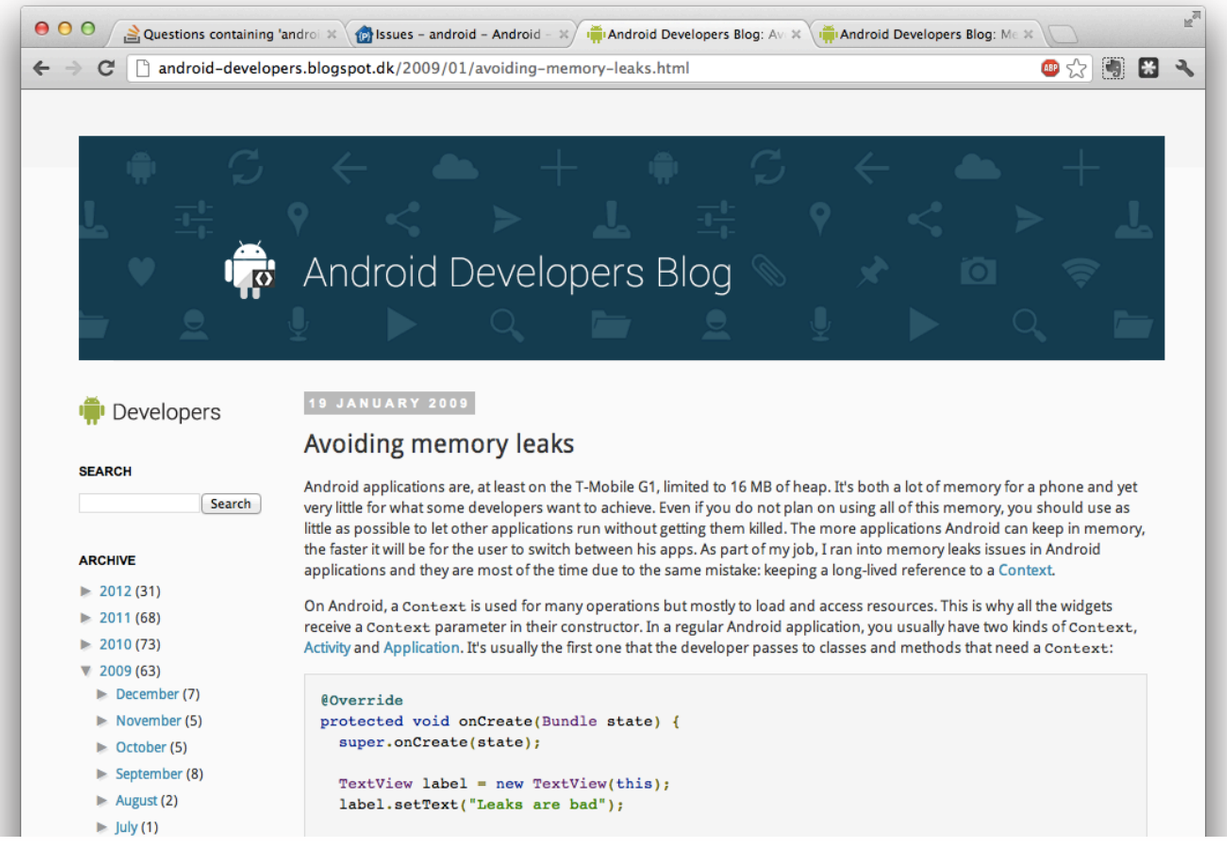


The expert recommendation …

"Do not keep long-lived references to a context-activity"



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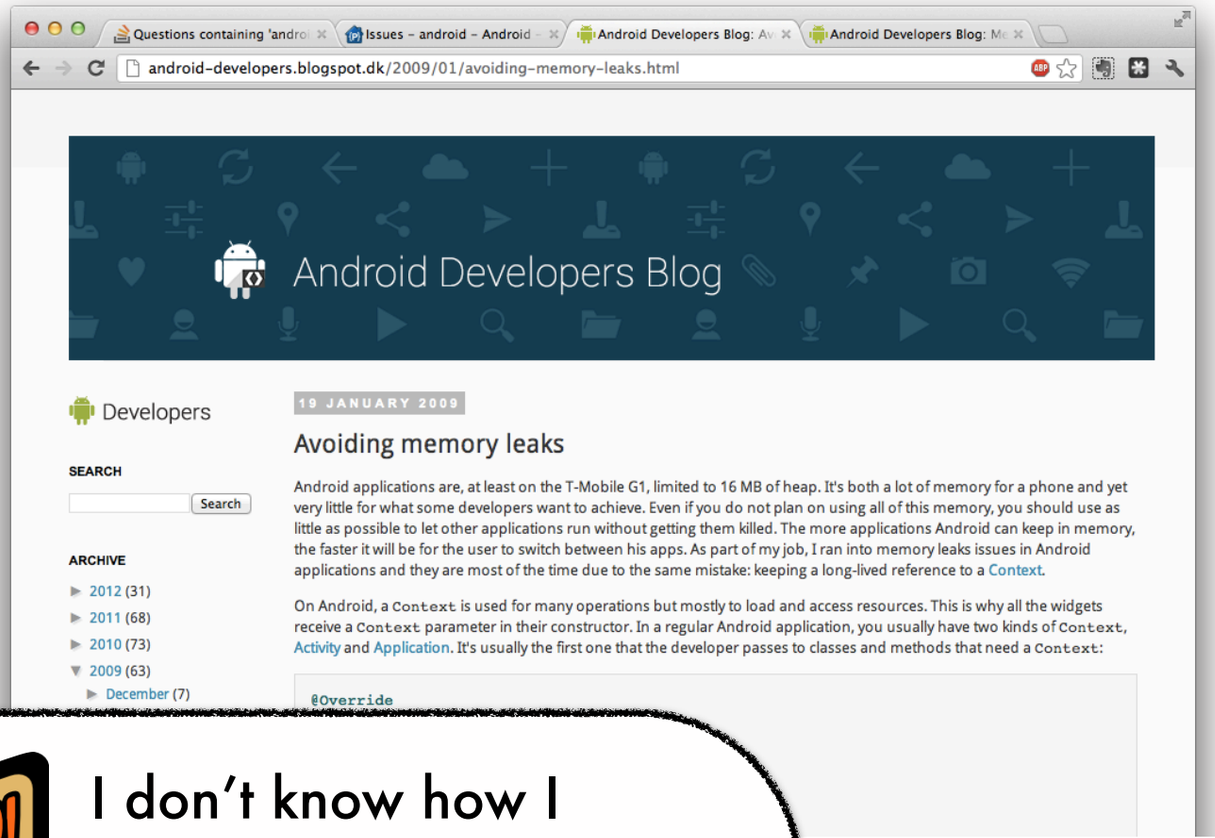

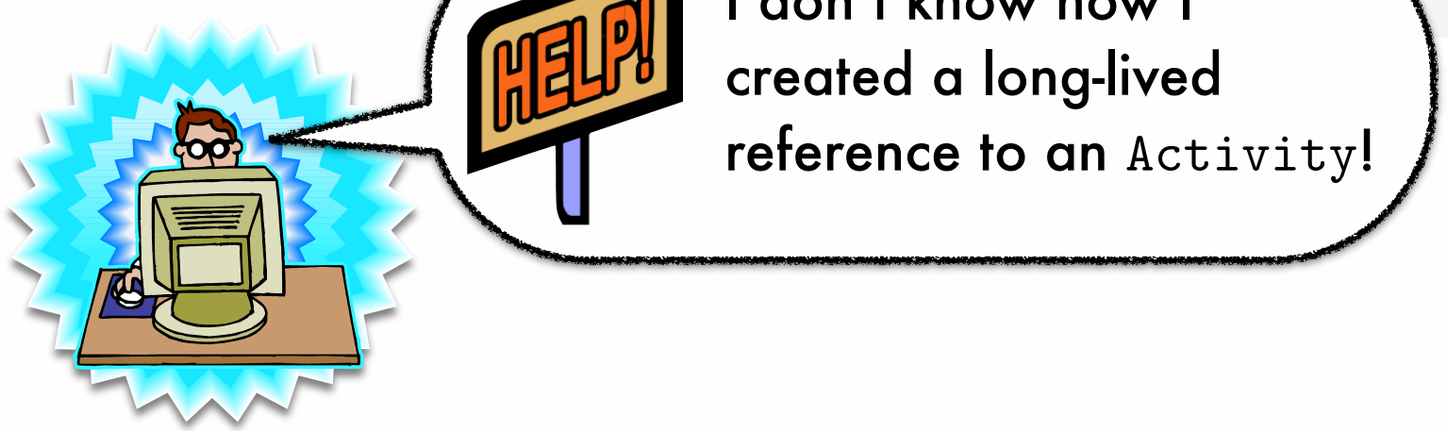

The expert recommendation …

"Do not keep long-lived references to a context-activity"

I don't know how I created a long-lived reference to an `Activity`!

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


Verification

The expert recommendation ...

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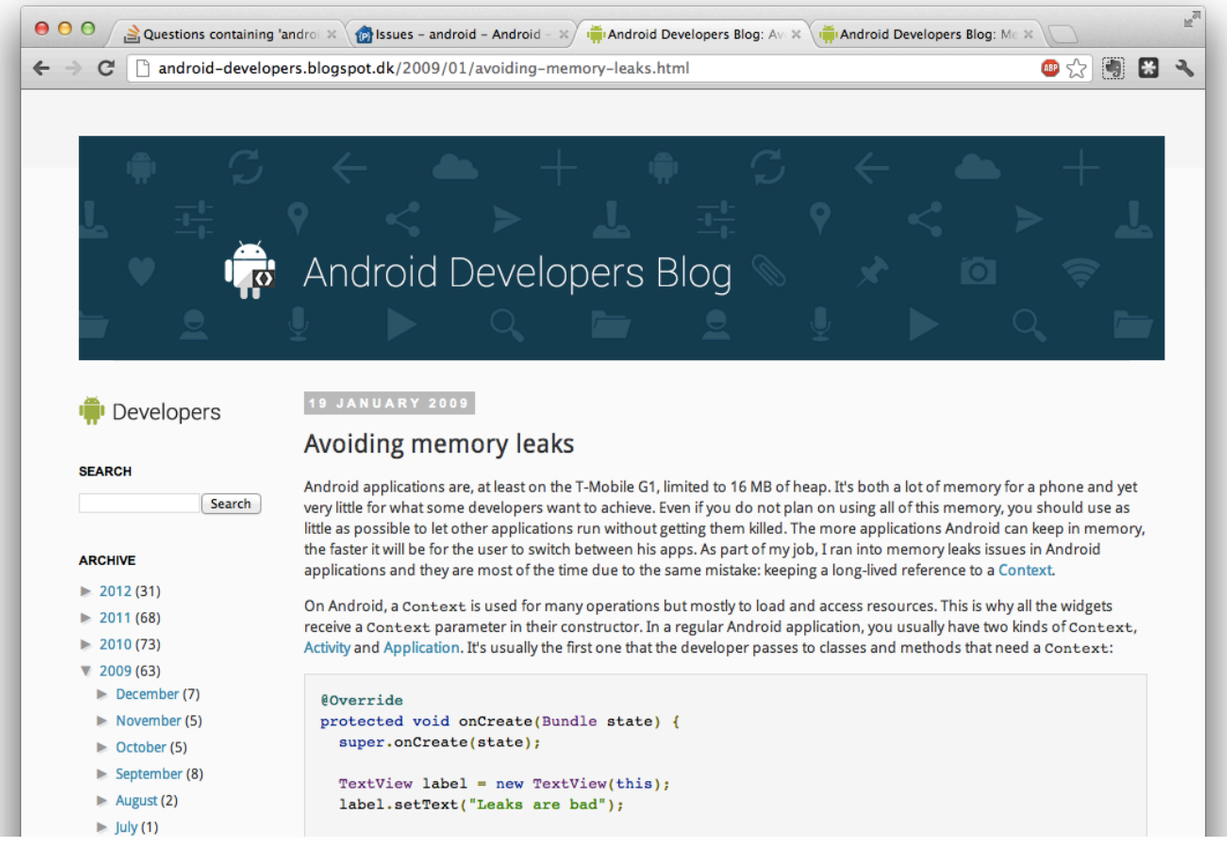

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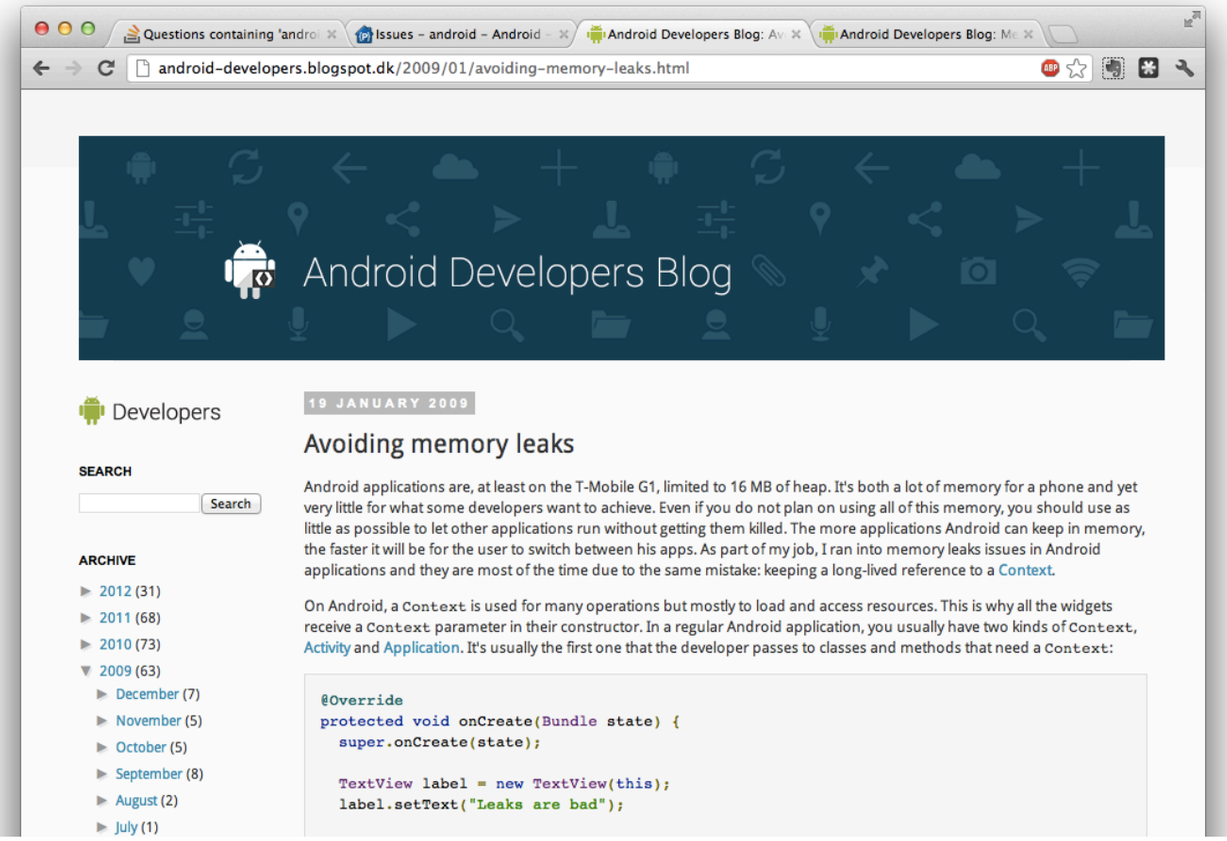

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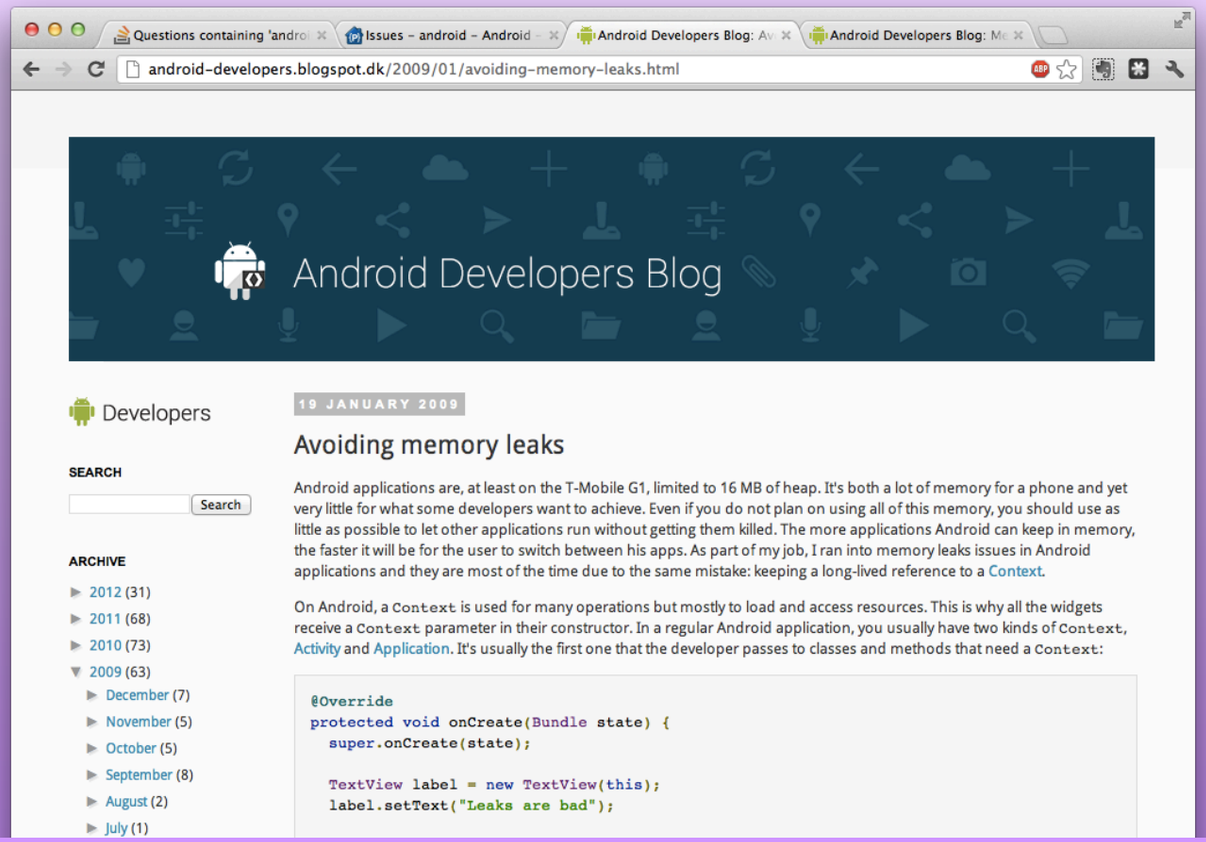

A Specific Property to Check:

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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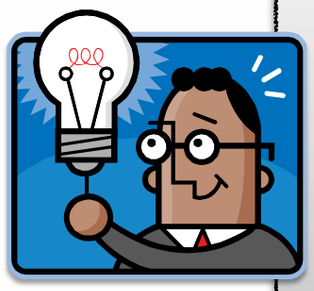

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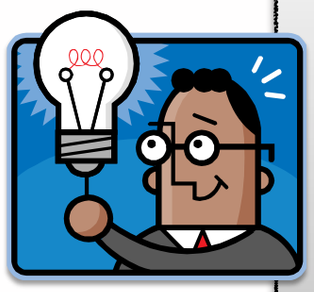

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Compute a points-to graph and look for such points-to paths

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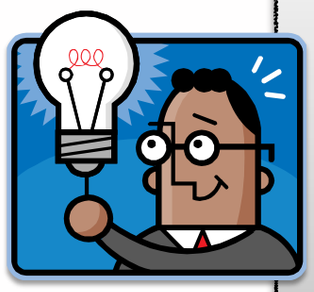

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This won't work because …

The well-known false alarm problem!

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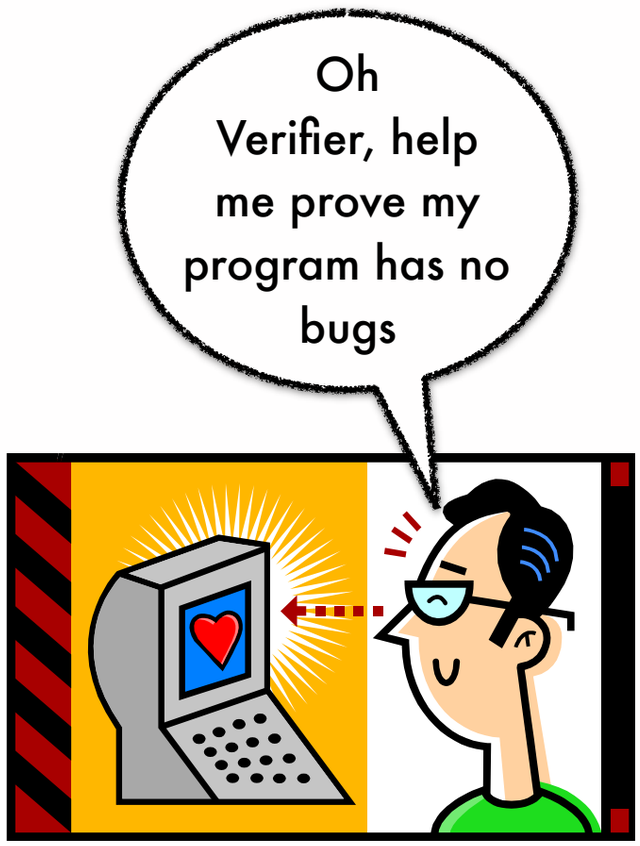

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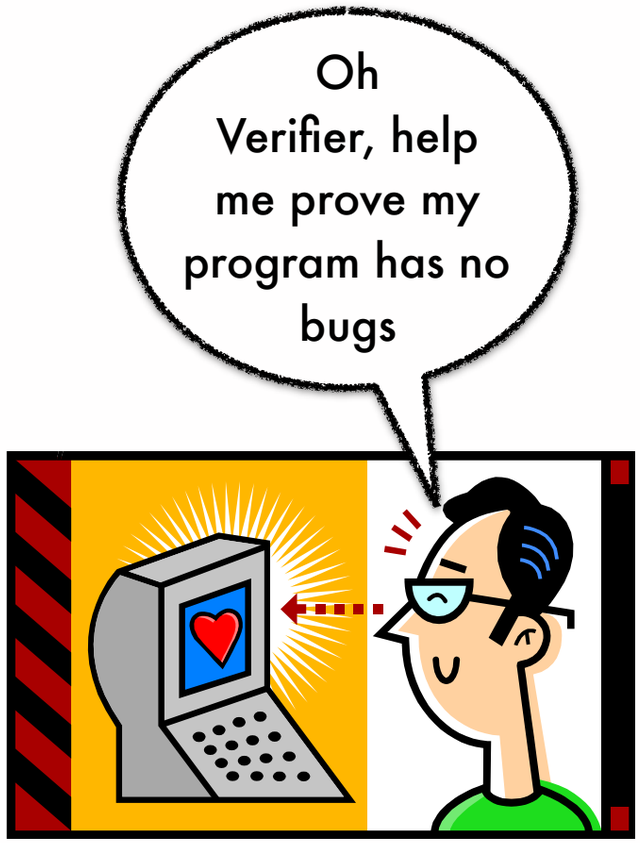

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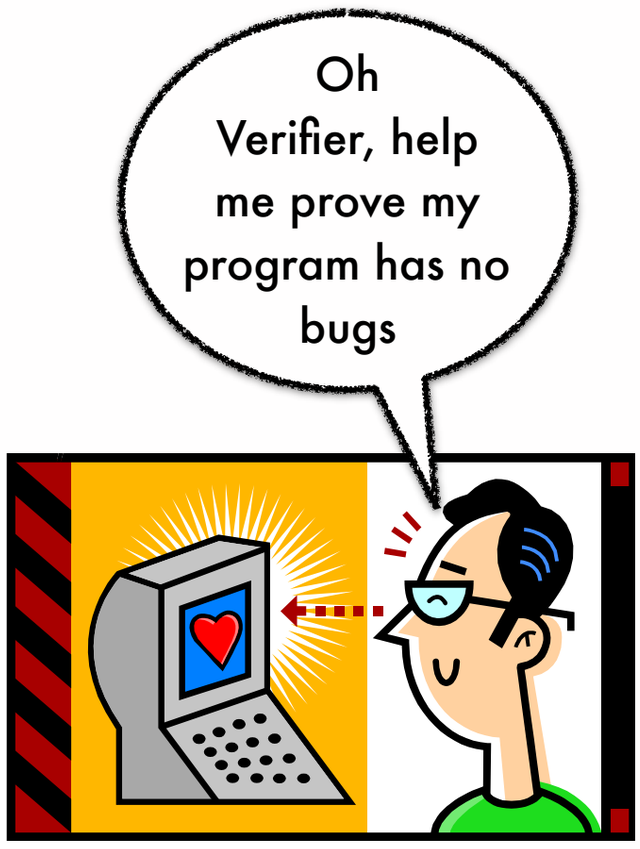
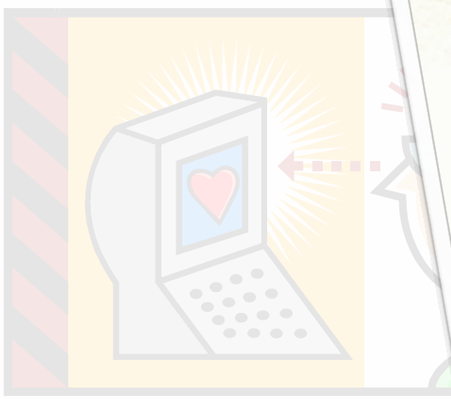


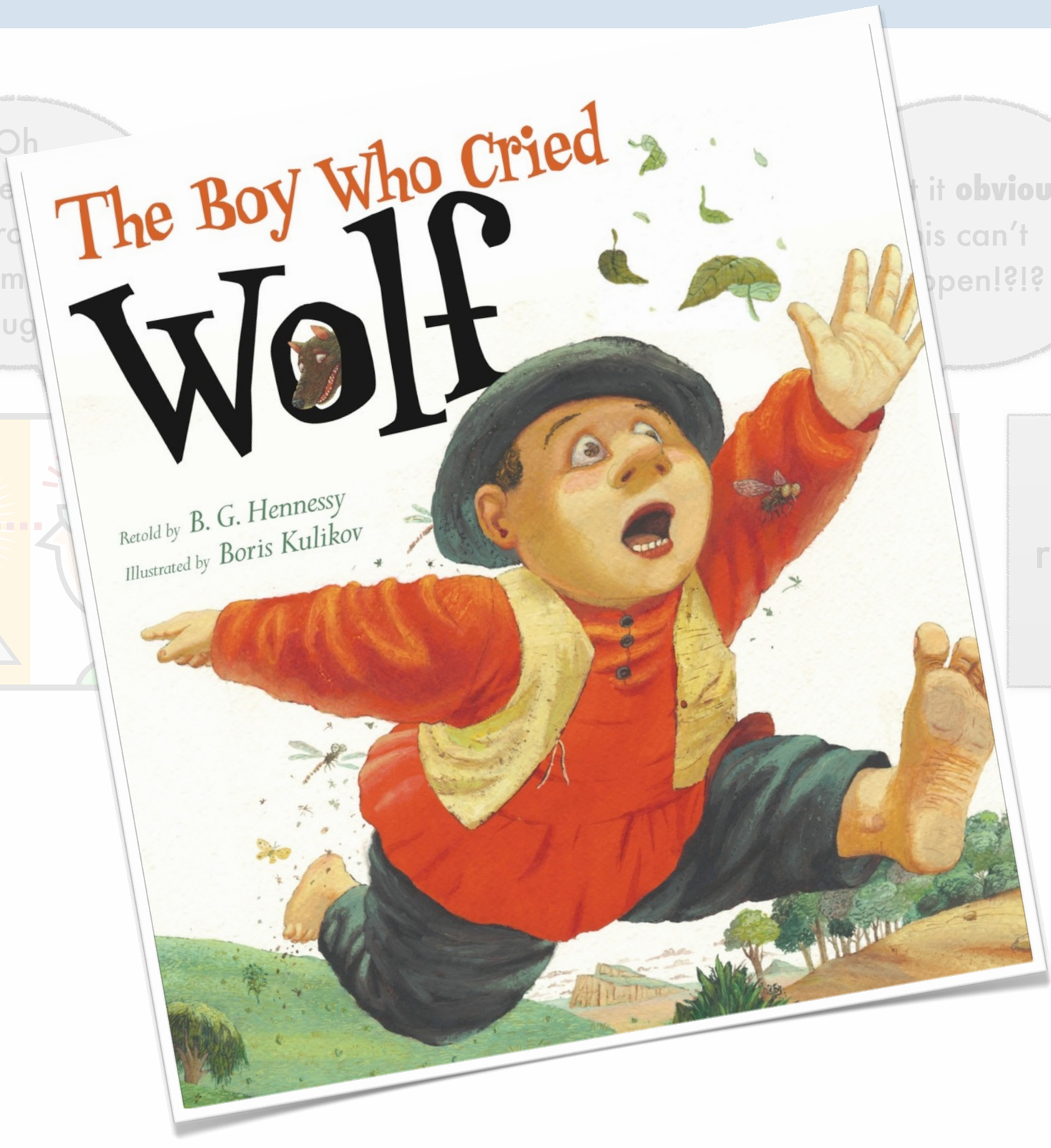
And noisily repeated over and over!

The well-known false alarm problem!

Oh
Verifie
me pro
program
bug

it **obvious**
is can't
pen!?!?





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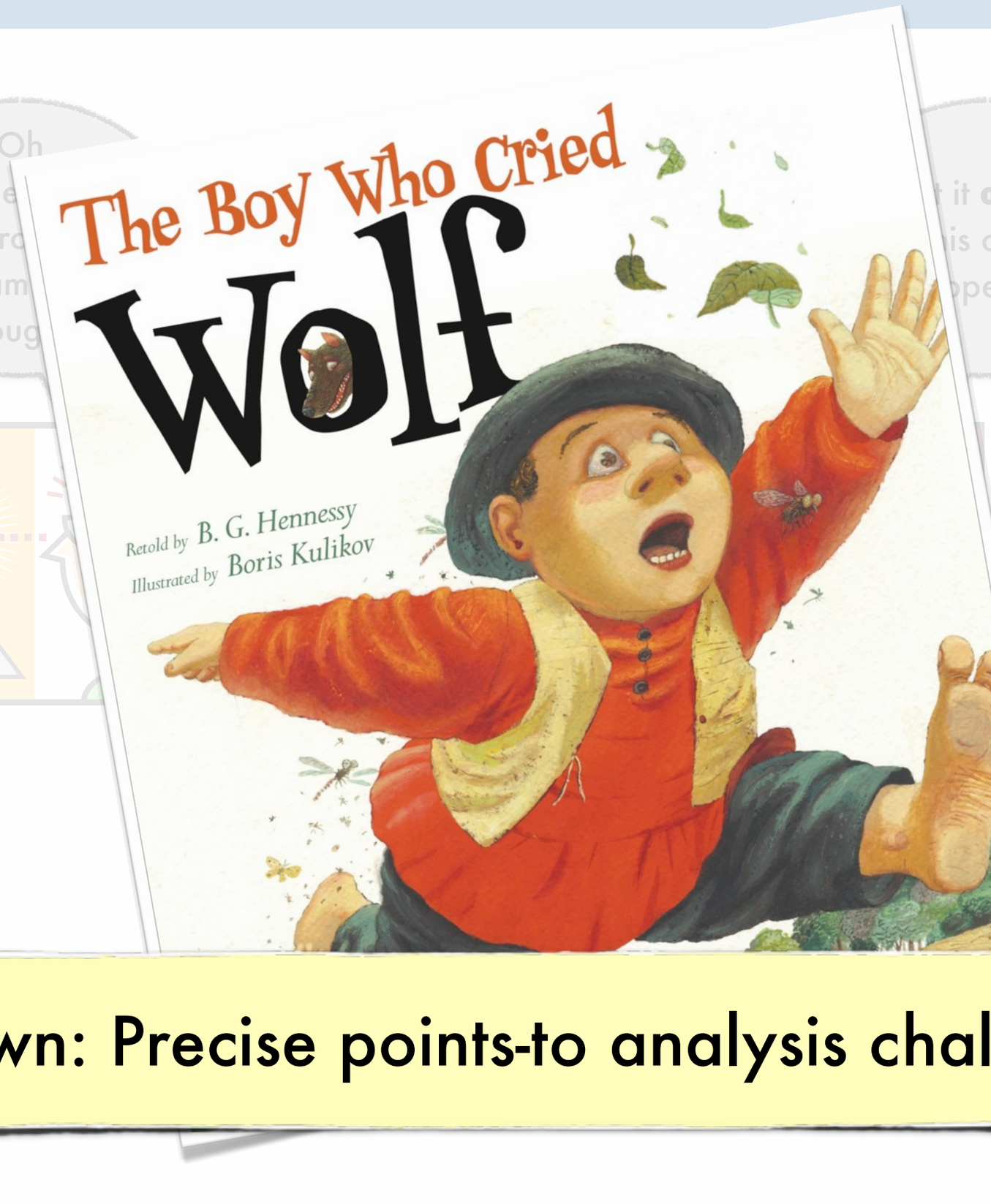

Known: Precise points-to analysis challenging

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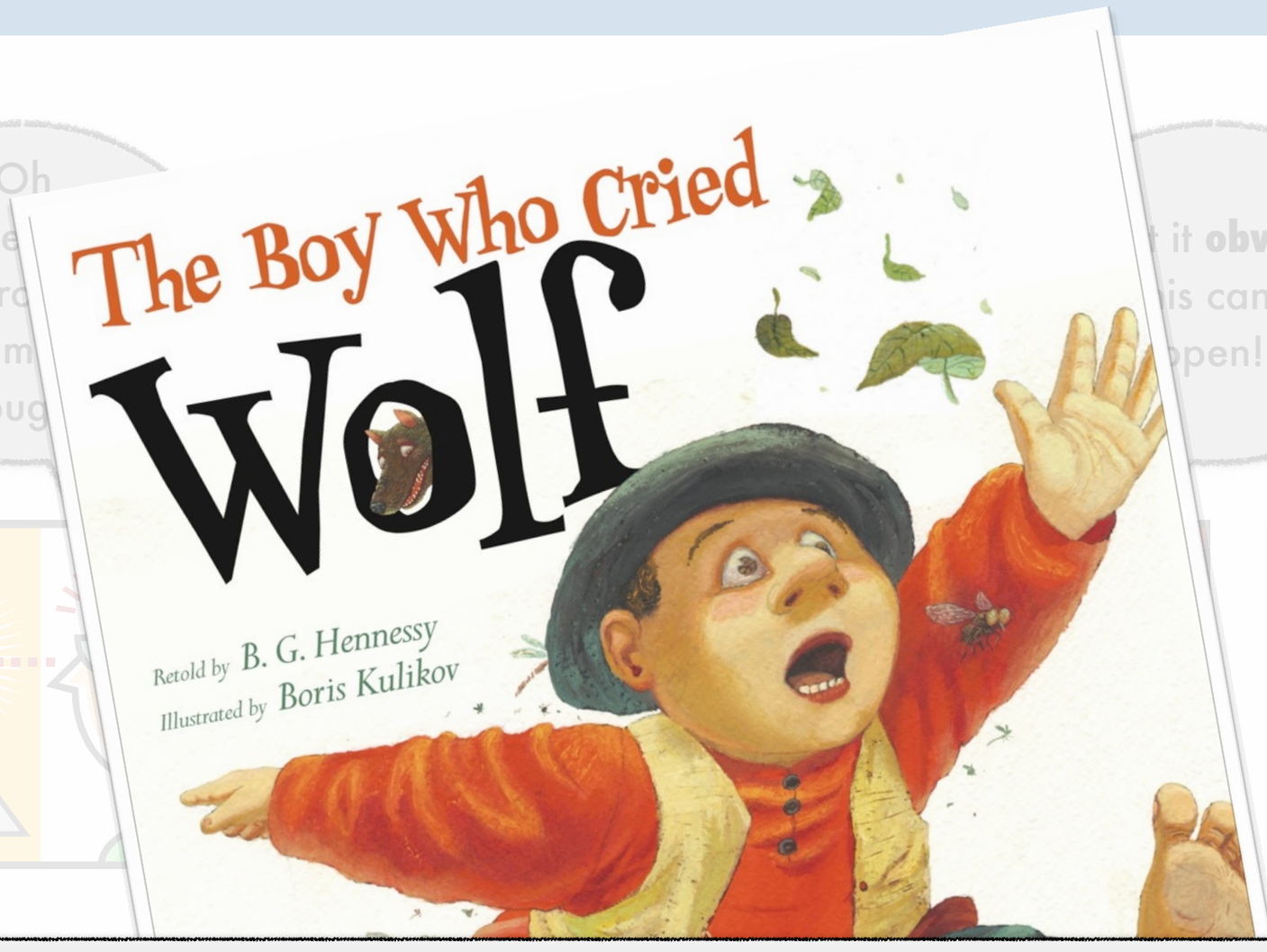

Hind (2001). "Pointer Analysis: Haven't We Solved This Problem Yet?"

- 75 papers, 9 PhD theses

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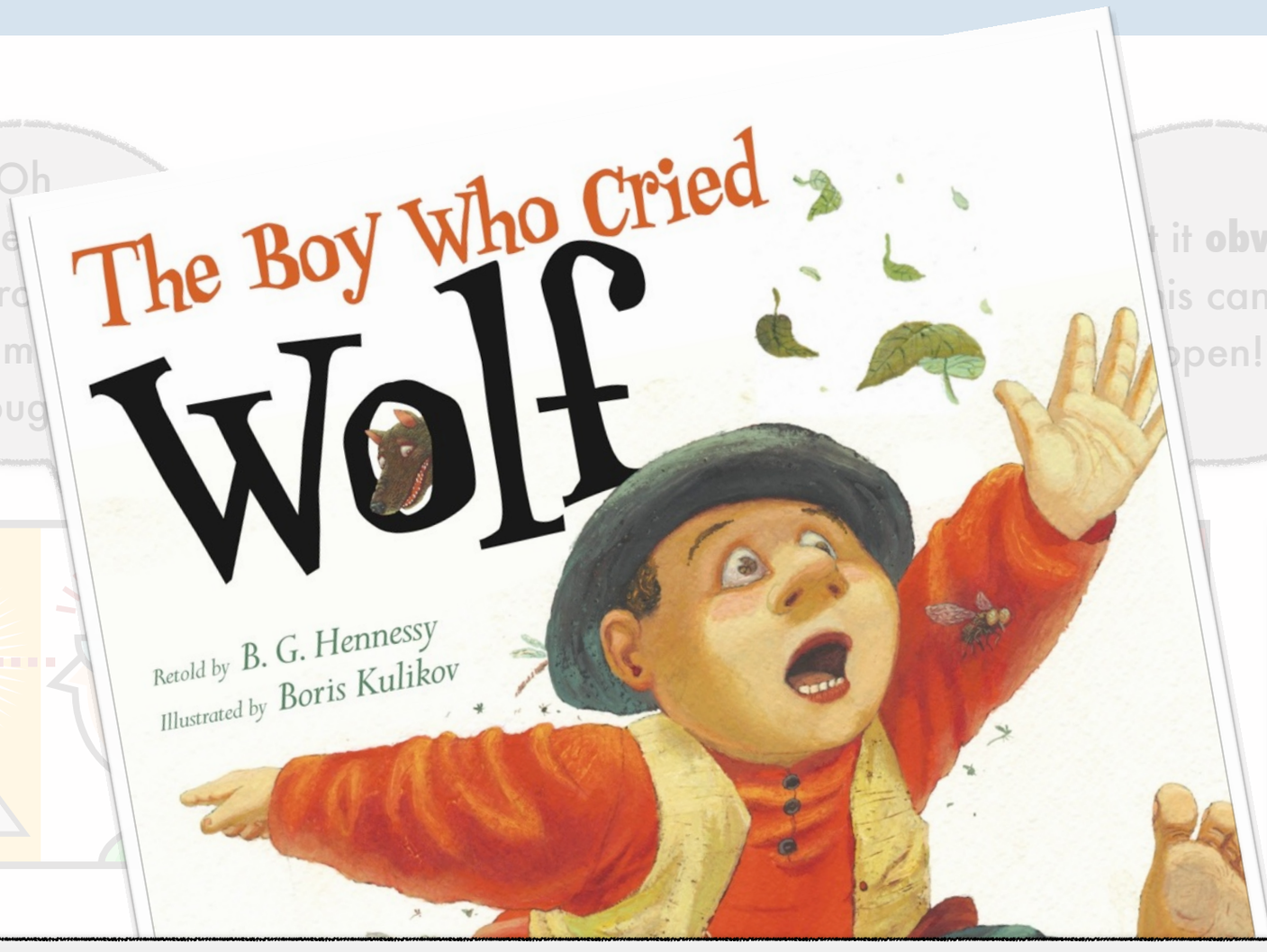

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Known: Precise points-to analysis ~~challenging~~

enough

impossible?


Verification

Perspective: The false alarm problem

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Verifier

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A "union" of tools and techniques (e.g., model checking, abstract interpretation)

Verifier

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Spec-ification

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✔

proof of no bug

or

witness to a bug

Perspective: The false alarm problem

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✔

Happy!

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Happy!

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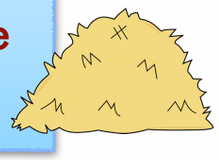
✘ alarms of maybe bugs



or

timeout

"bound-out"

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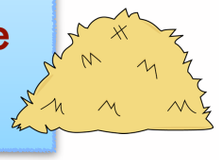
✘ alarms of maybe bugs



or

timeout "bound-out"

Unhappy but inevitable. Research work to minimize

Perspective: The false alarm problem

A "union" of tools and techniques (e.g., model checking, abstract interpretation)

Spec-ification

Program

Verifier

✔

proof of no bug

or

witness to a bug

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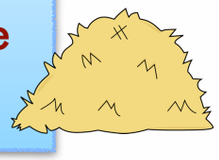

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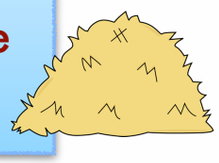

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This talk: Applied to heap reachability

Unhappy but inevitable. Research work to minimize

Different classes of tools make different trade-offs: Recognize strength in combining MC-AI approaches

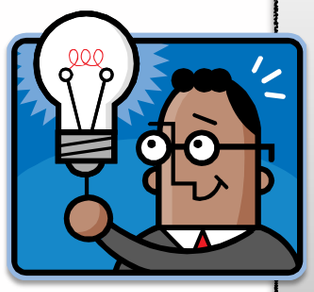
A candidate for statically answering, "Is there an `Activity` leak?"

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

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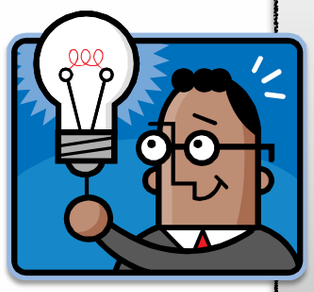

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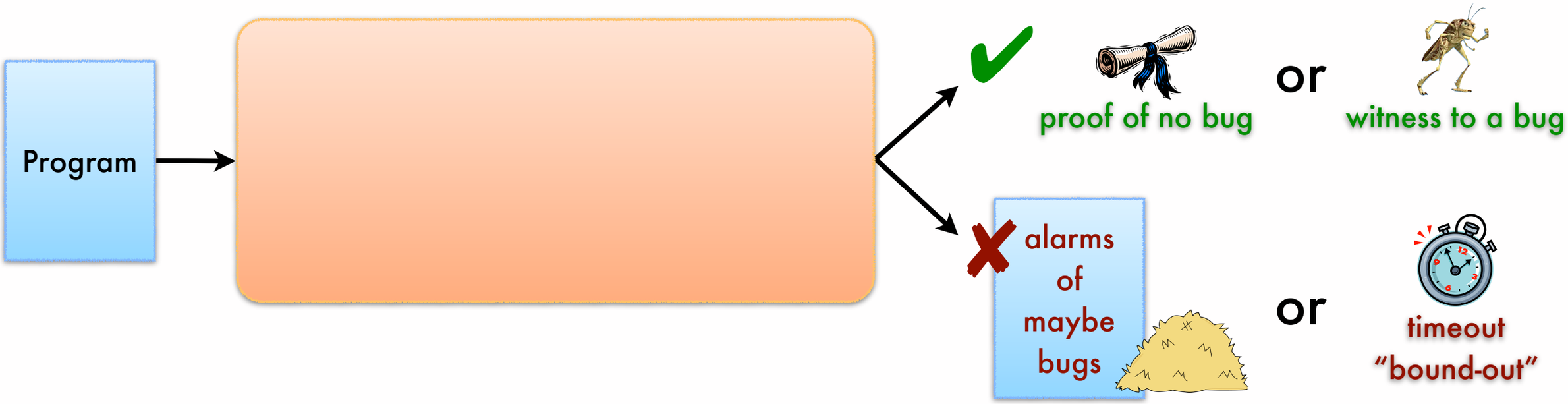
Let's make it work!

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



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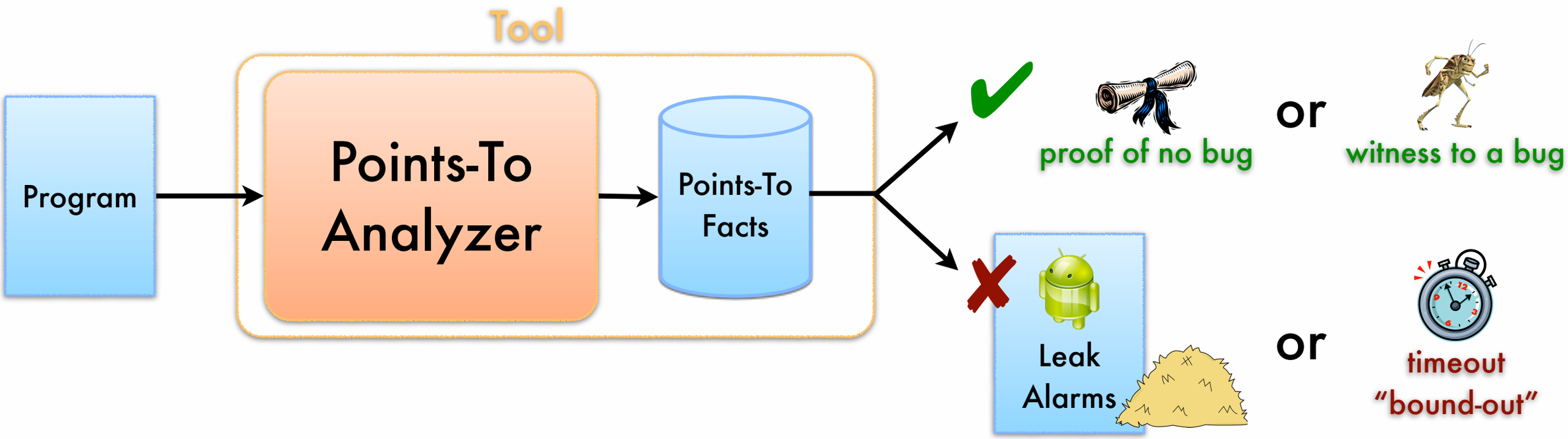

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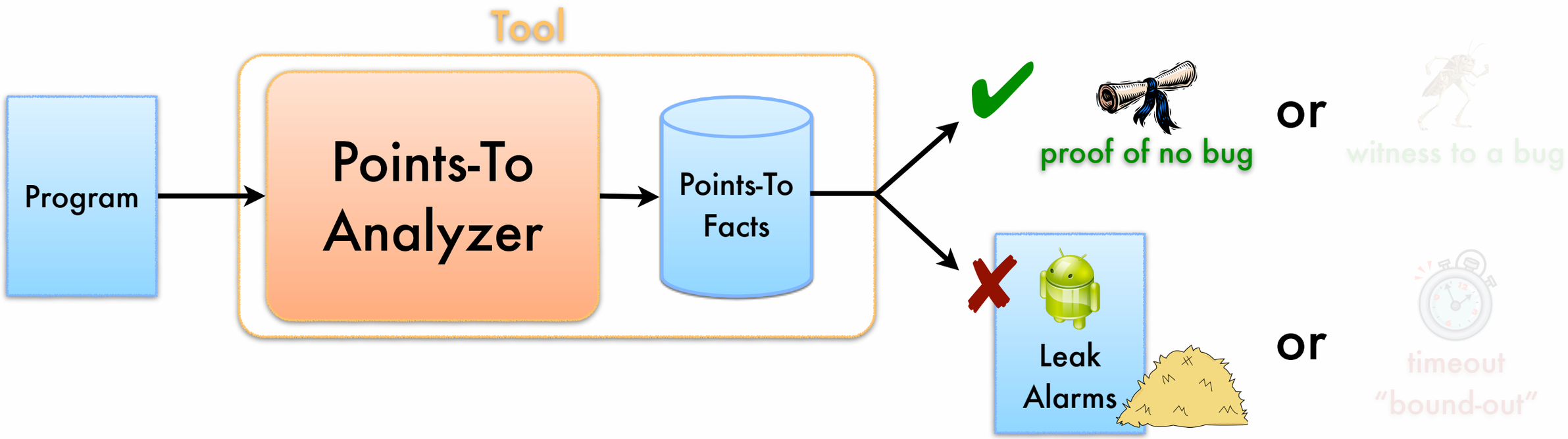

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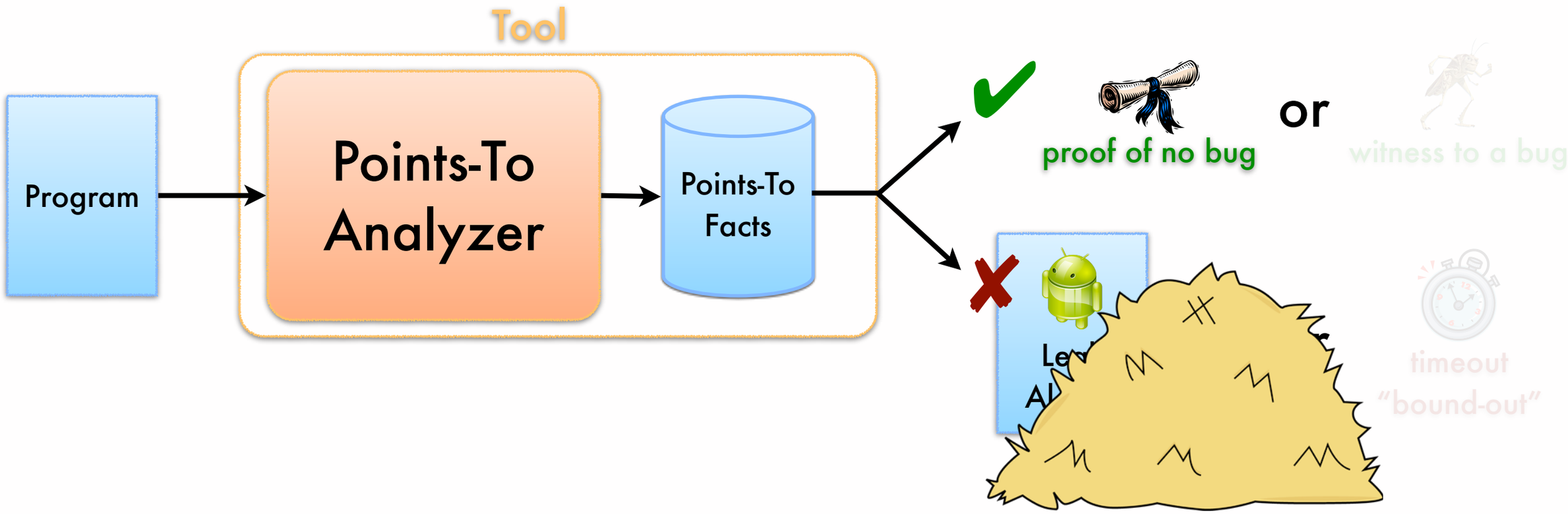

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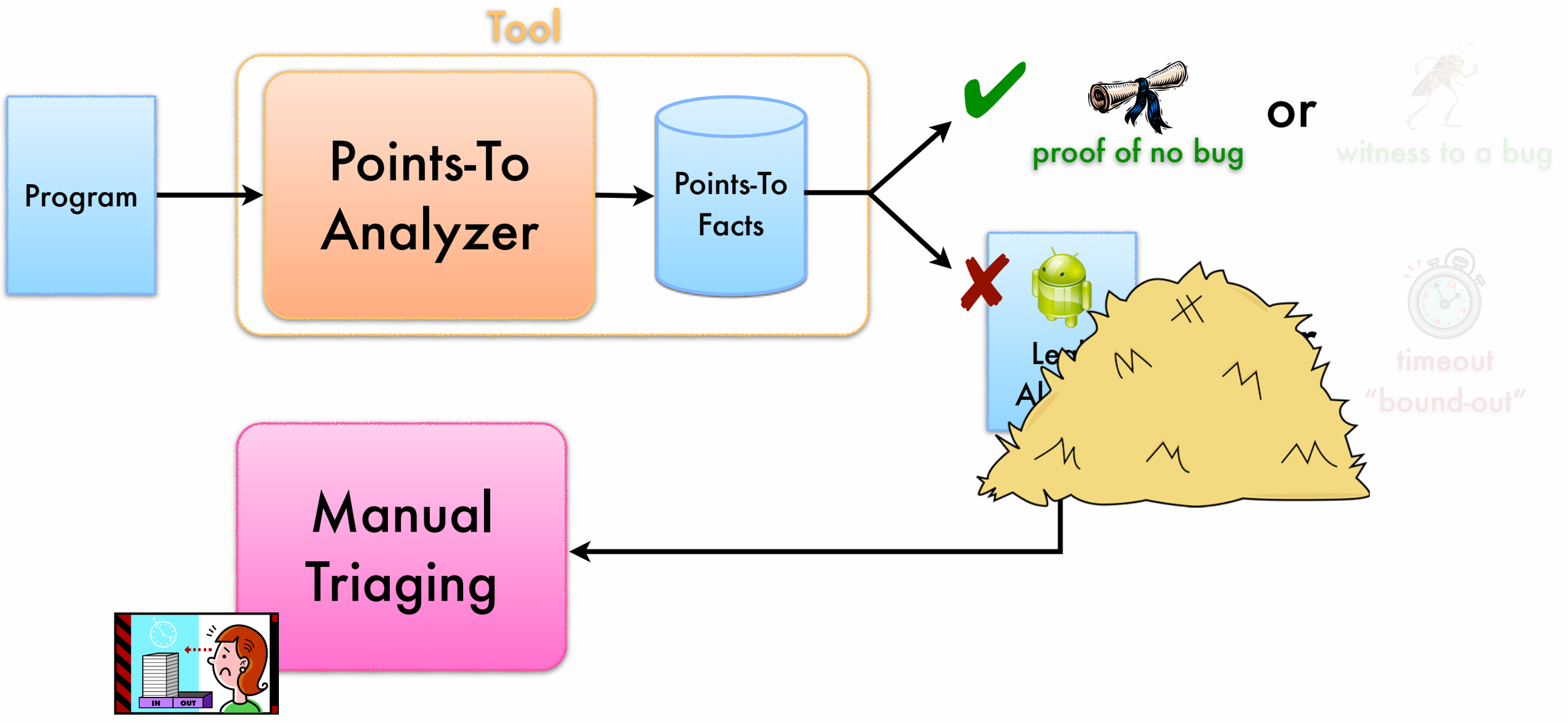

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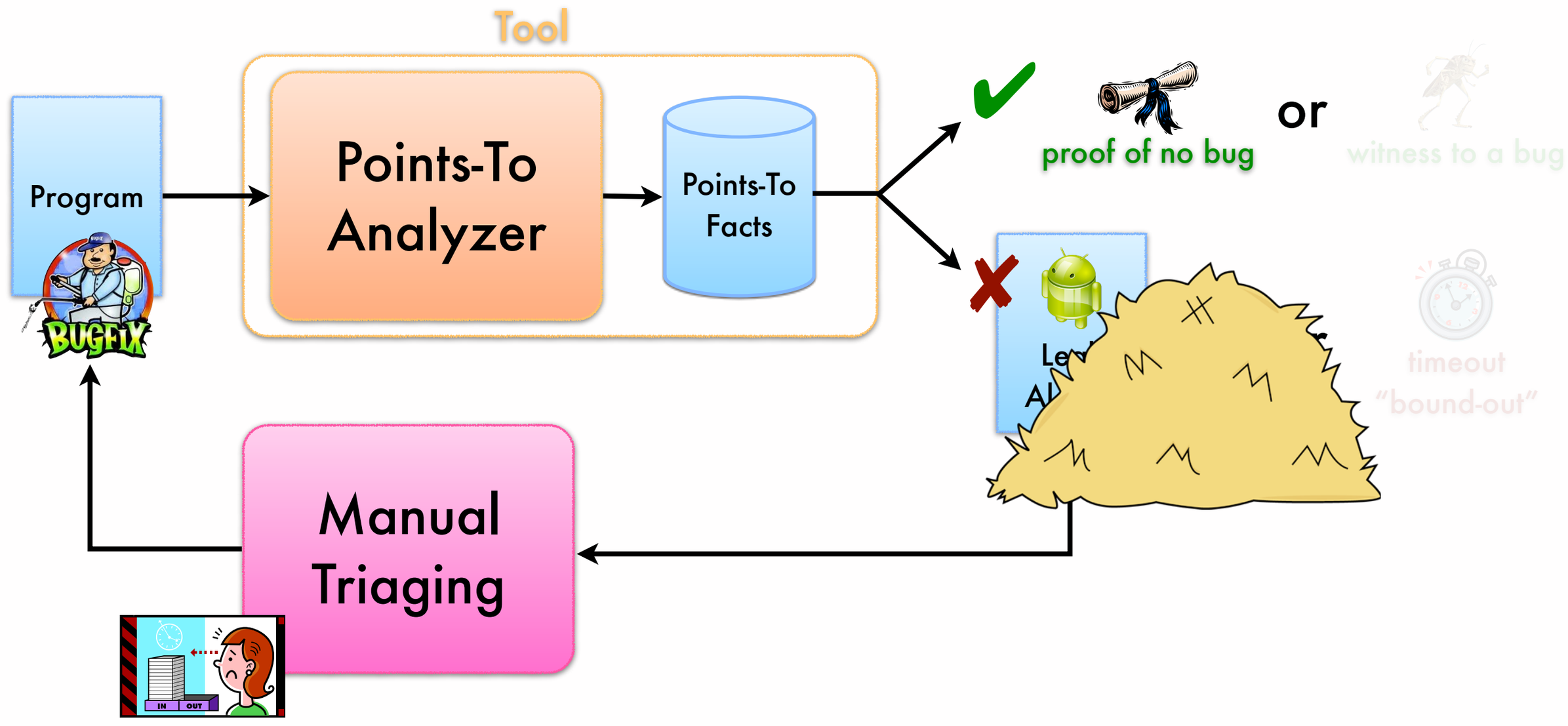

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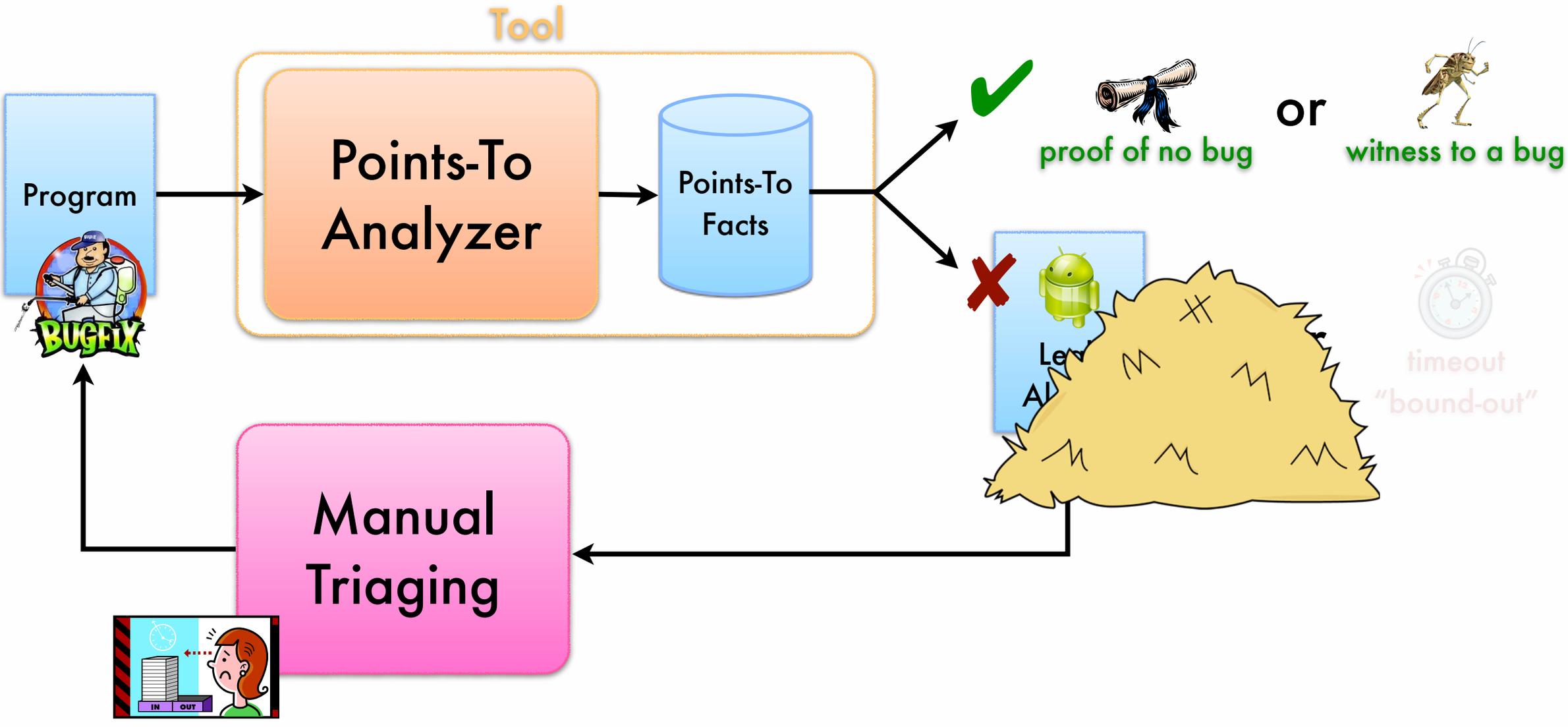

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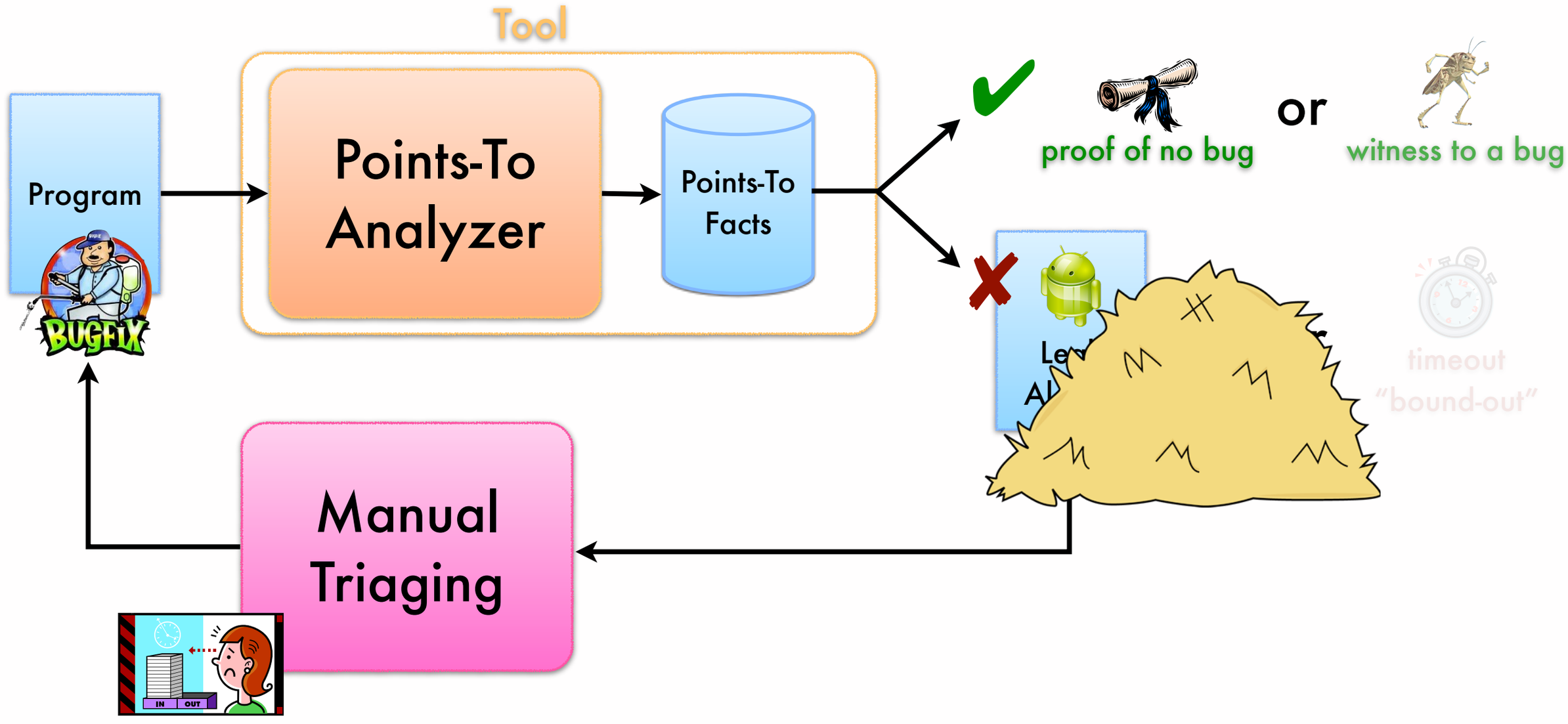


Prove alarms false with a witness search

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

Tool

Program

Points-To Analyzer

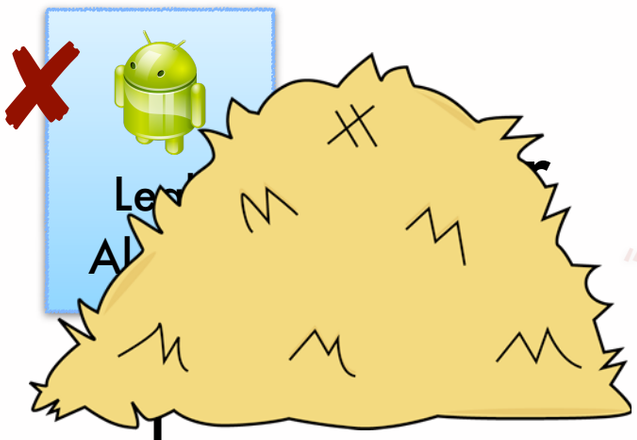
Points-To Facts

✔ proof of no bug

or

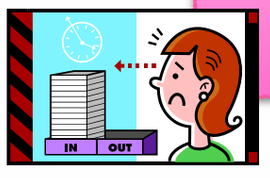
witness to a bug

✘



timeout "bound-out"

Manual Triaging

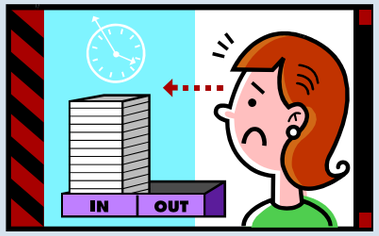


Proof Obligation User-Query
[Dillig, Dillig, Aiken (2012)]

Alarm Clustering
[Lee, Lee, Yi (2012)]

Prove alarms false with a witness search

Manual triage for heap reachability reports



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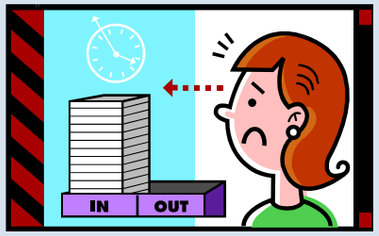

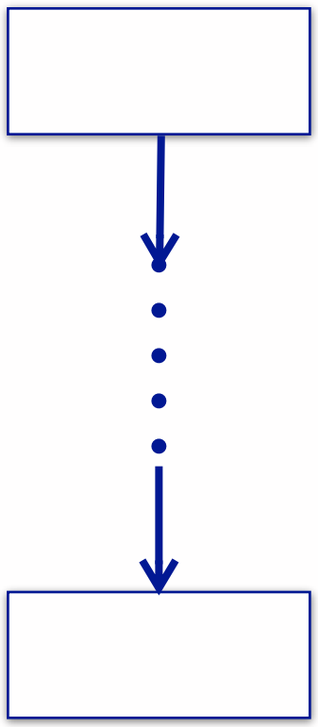

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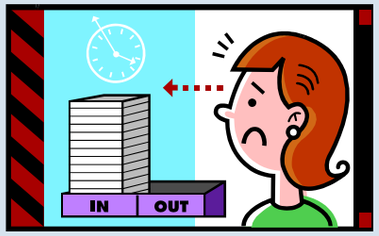

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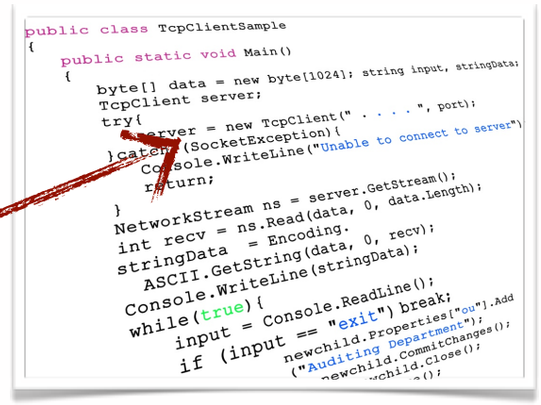
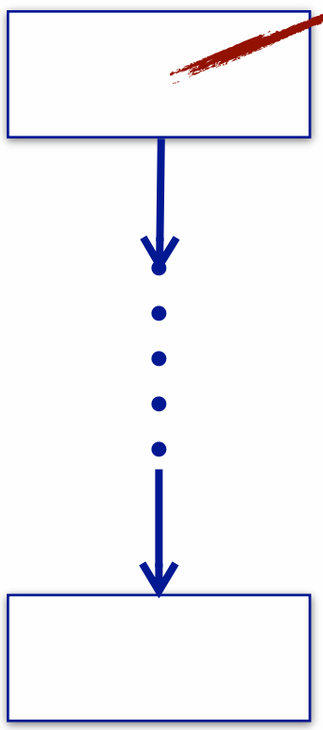


```
public class TcpClientSample
{
    public static void Main()
    {
        byte[] data = new byte[1024]; string input, stringData;
        TcpClient server;
        try{
          server = new TcpClient(" . . . . ", port);
        }catch(SocketException){
          Console.WriteLine("Unable to connect 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



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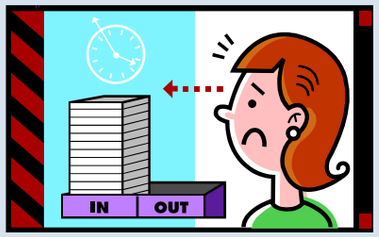

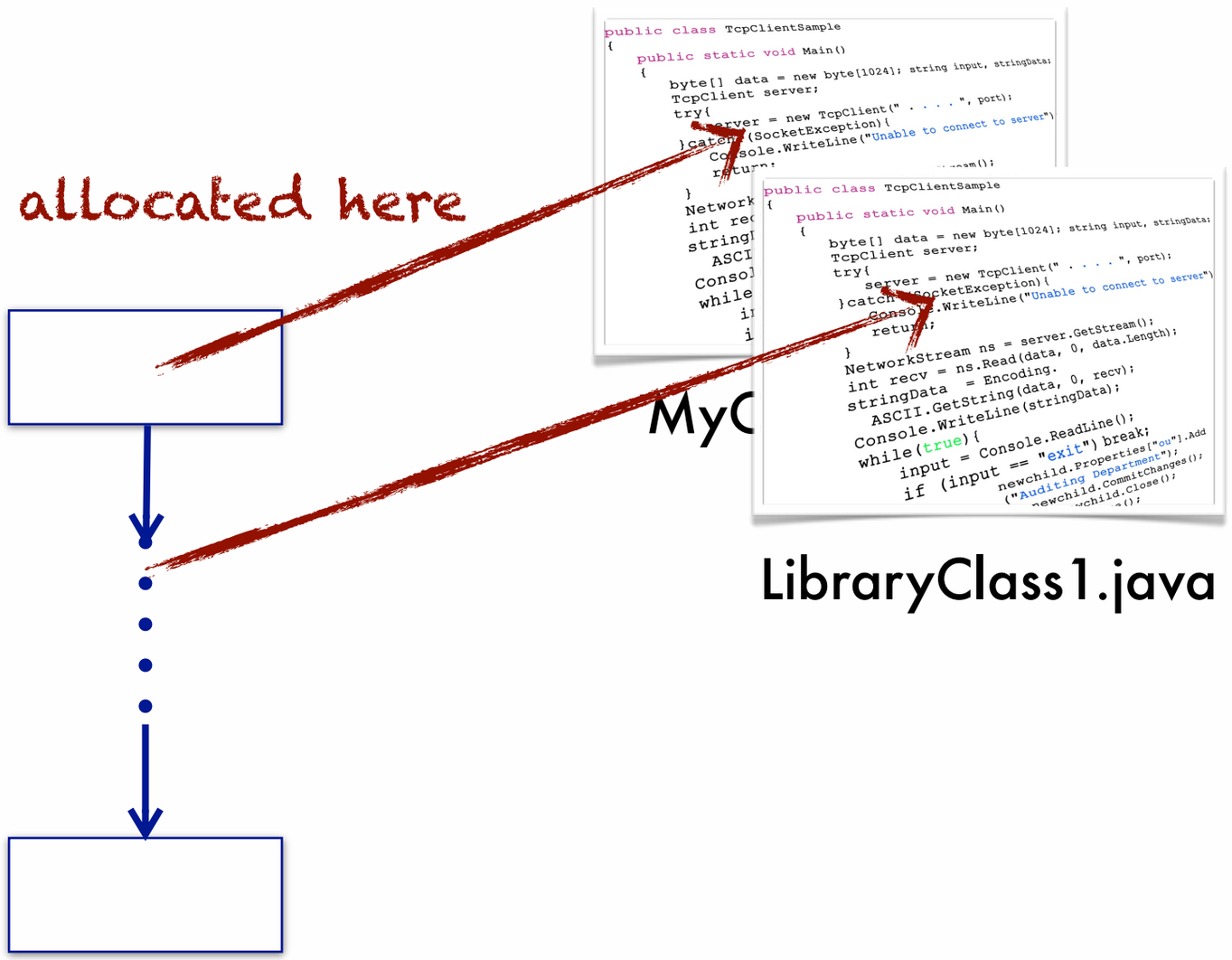

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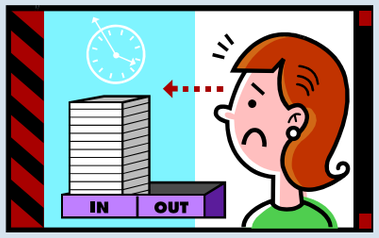

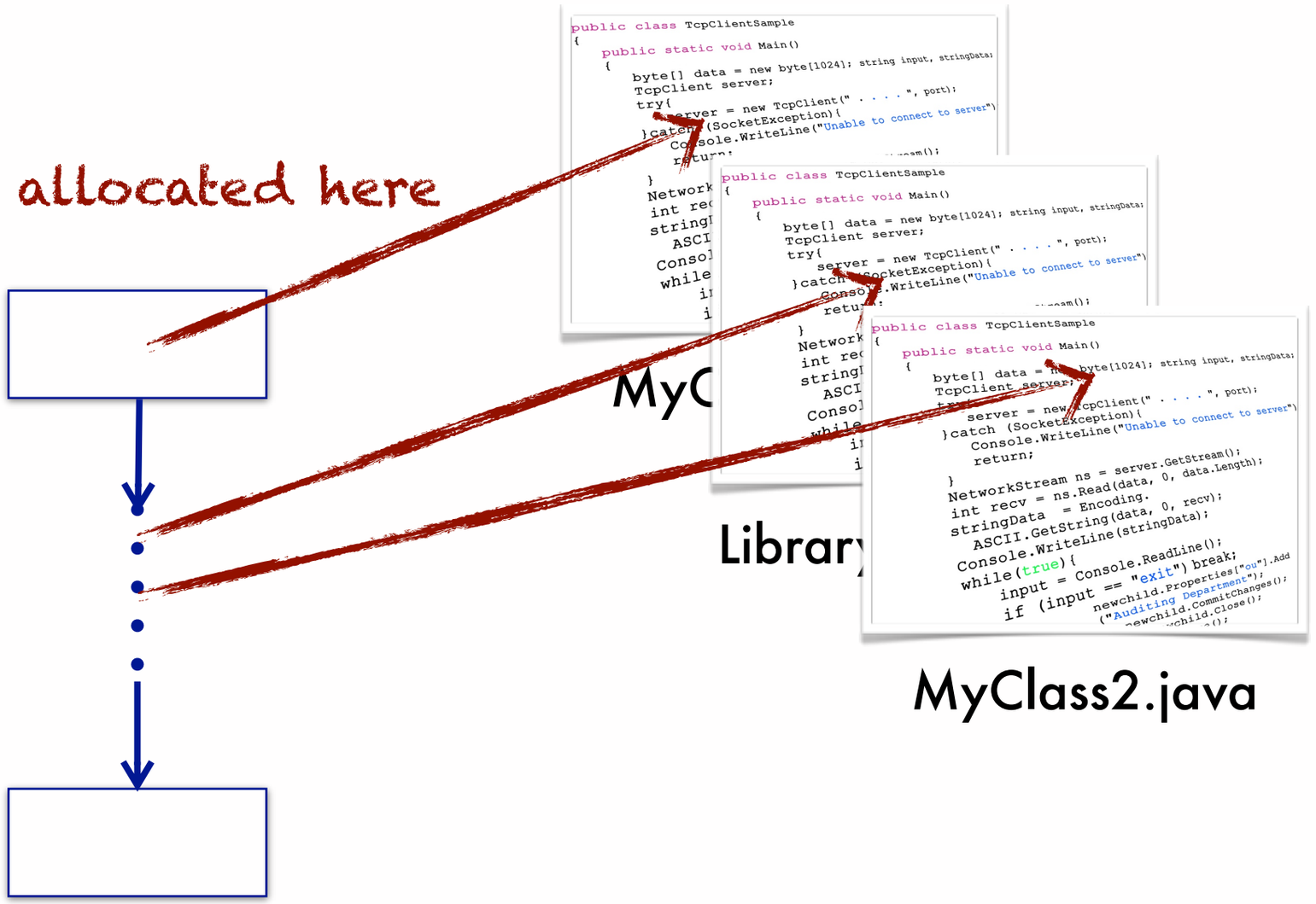

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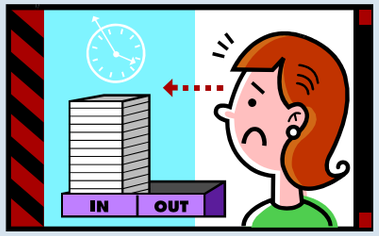

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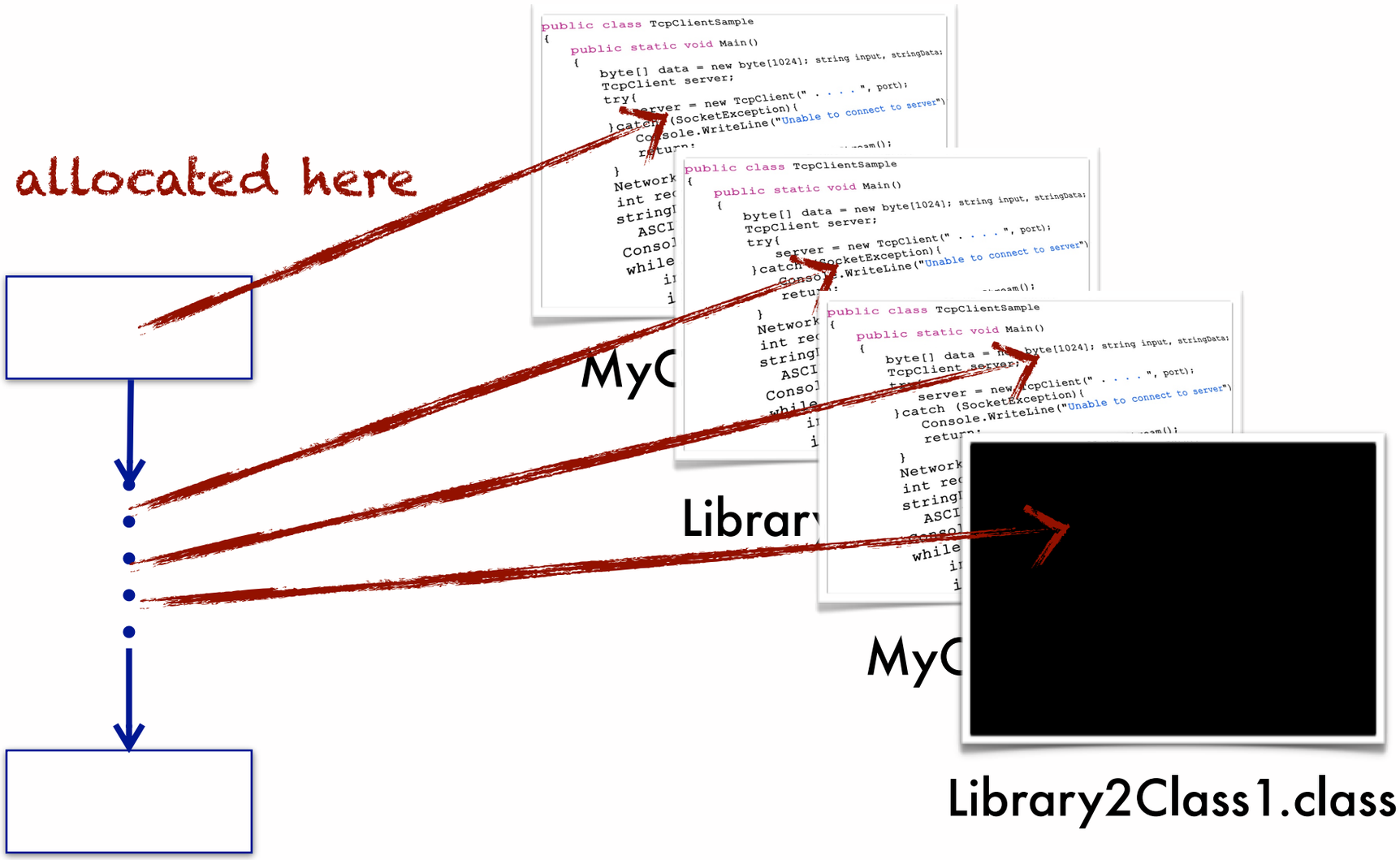

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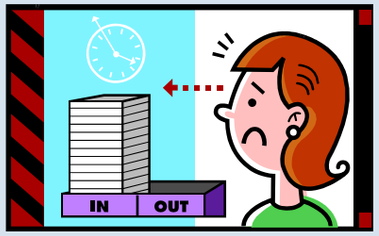


allocated here

MyC

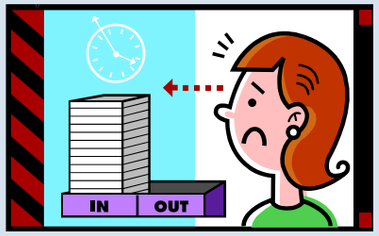
Library

MyC

Library

java.util.HashMap.class

Manual triage for heap reachability reports



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MyC

Library

MyC

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java.util.

MyClass3.java

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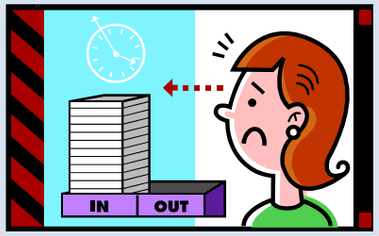
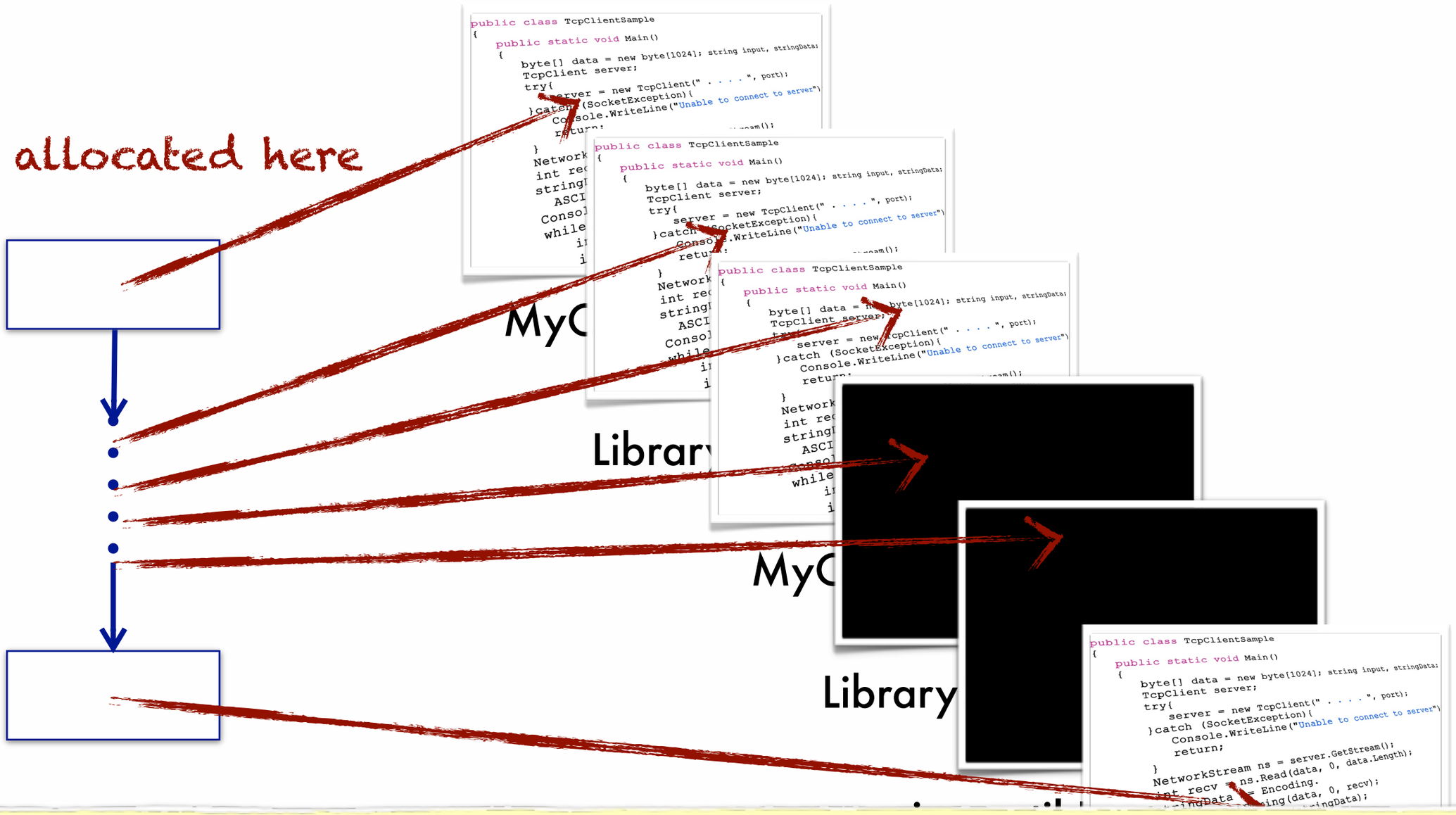
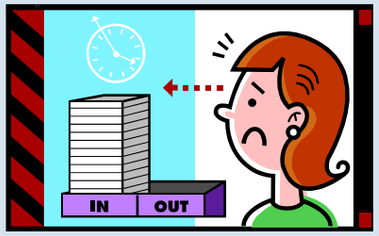




Get abstract heap path + allocation sites

Assuming the user starts to triage an alarm …



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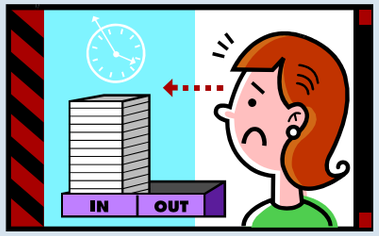

What does the user need to do? He starts at, say, line 142 and traces back to see if a bug is possible given what's happening.

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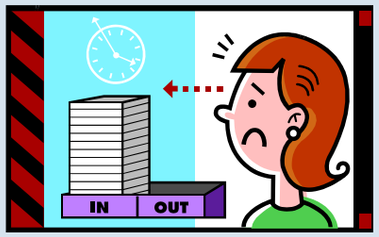

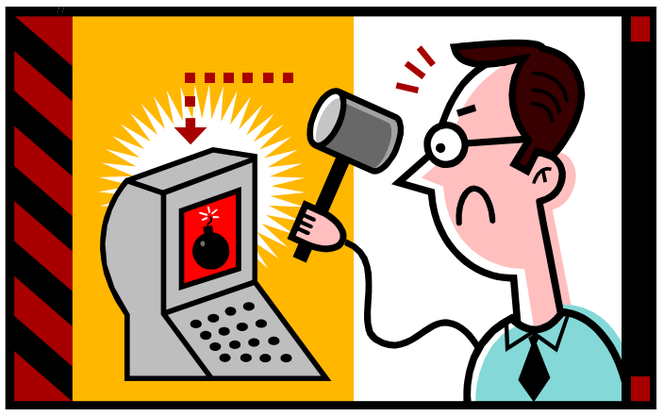

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We can do this with analysis!

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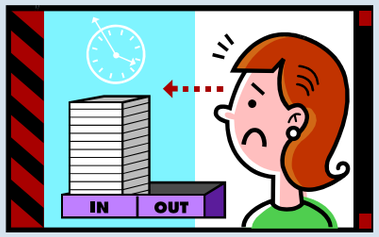

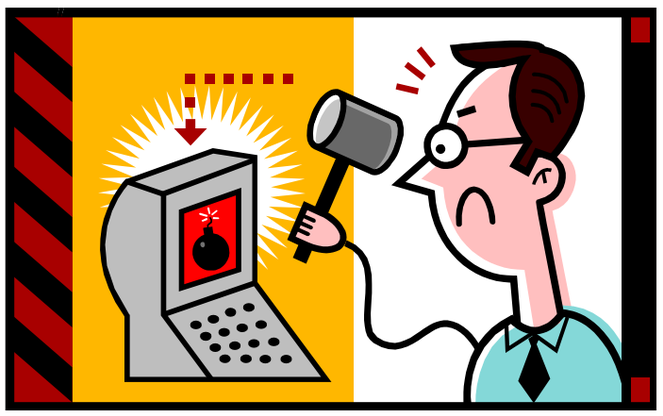

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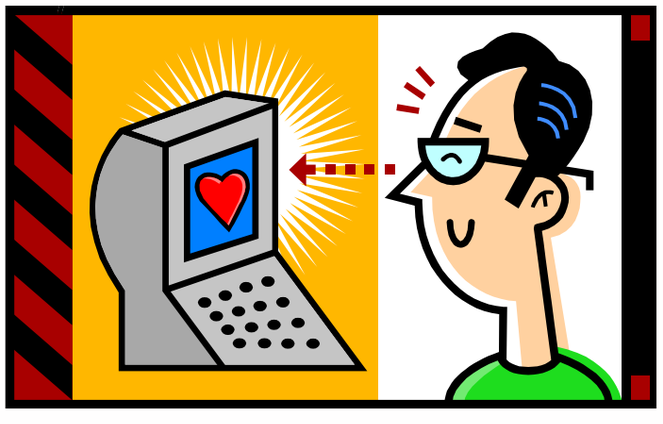
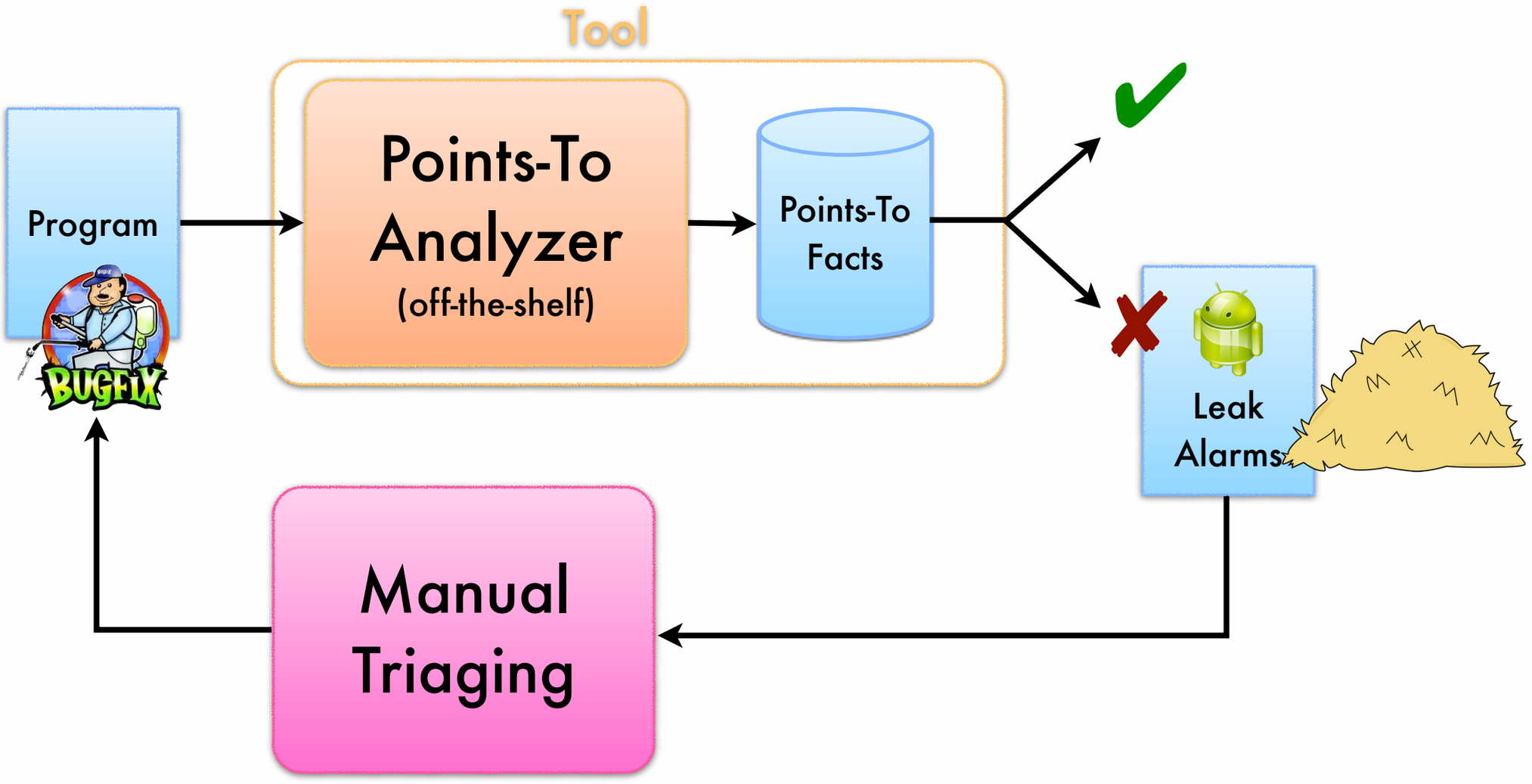


If we filter most false alarms, the user can triage more quickly and get to true bugs earlier (without frustration).

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



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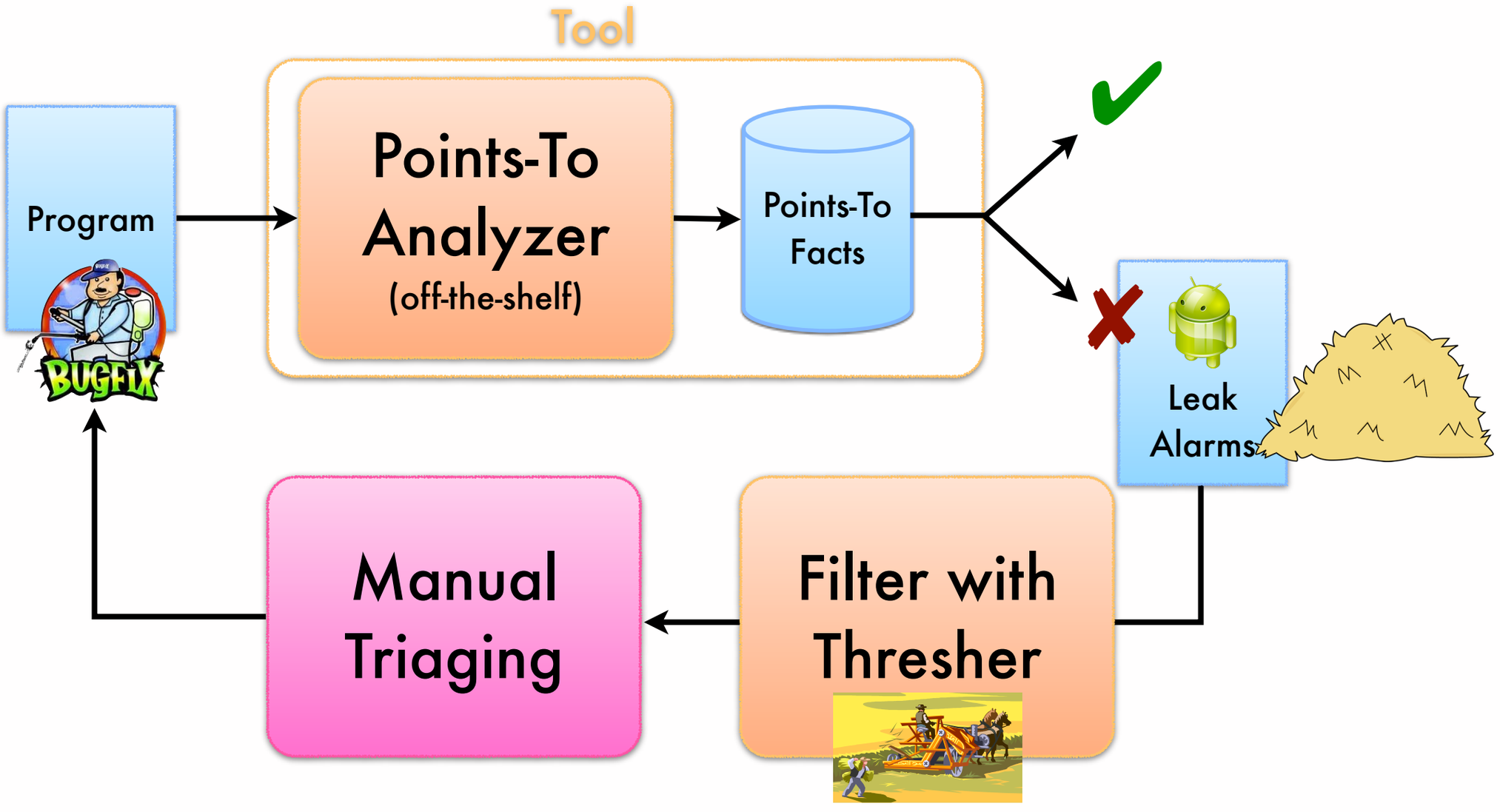

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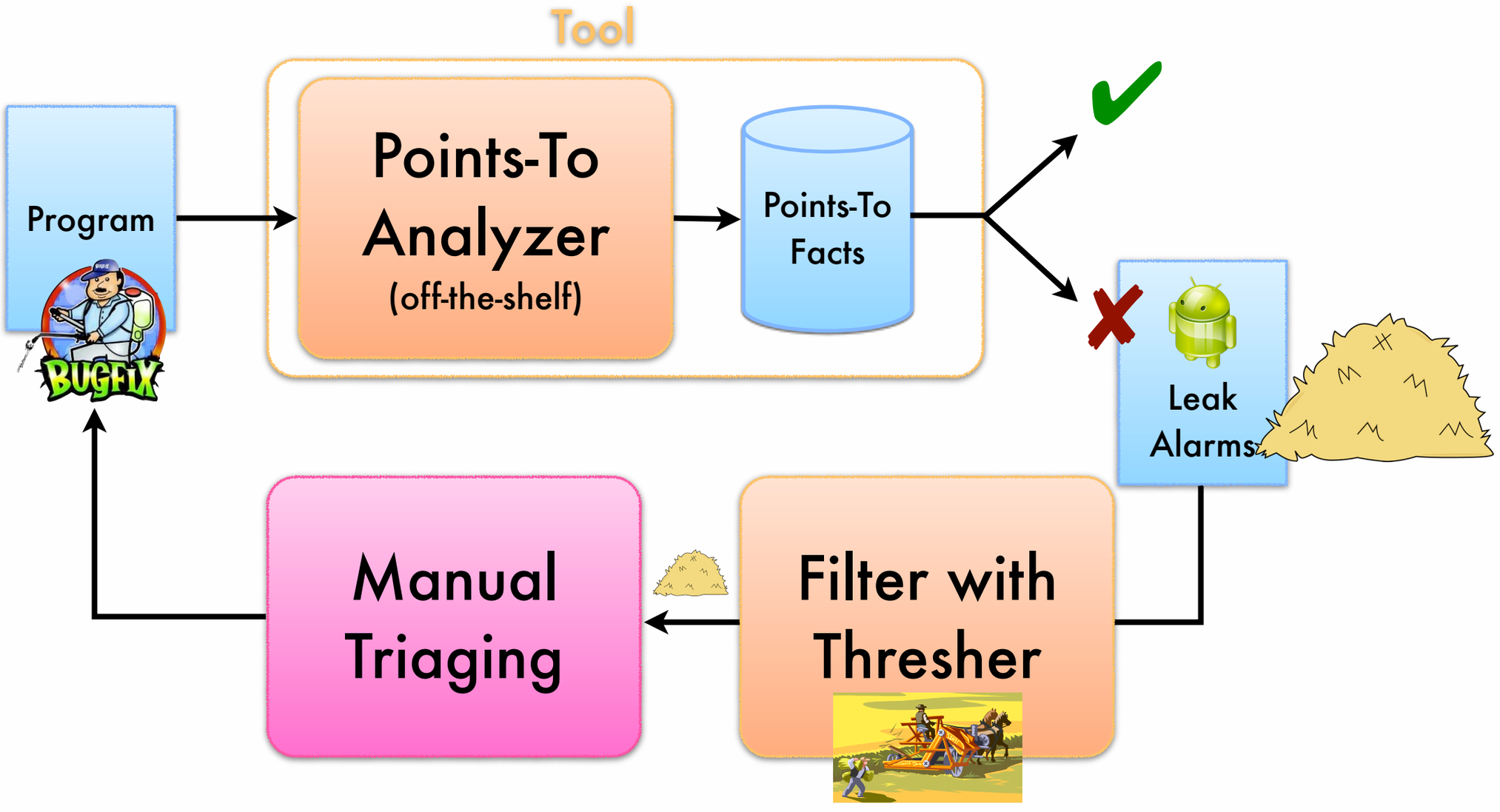

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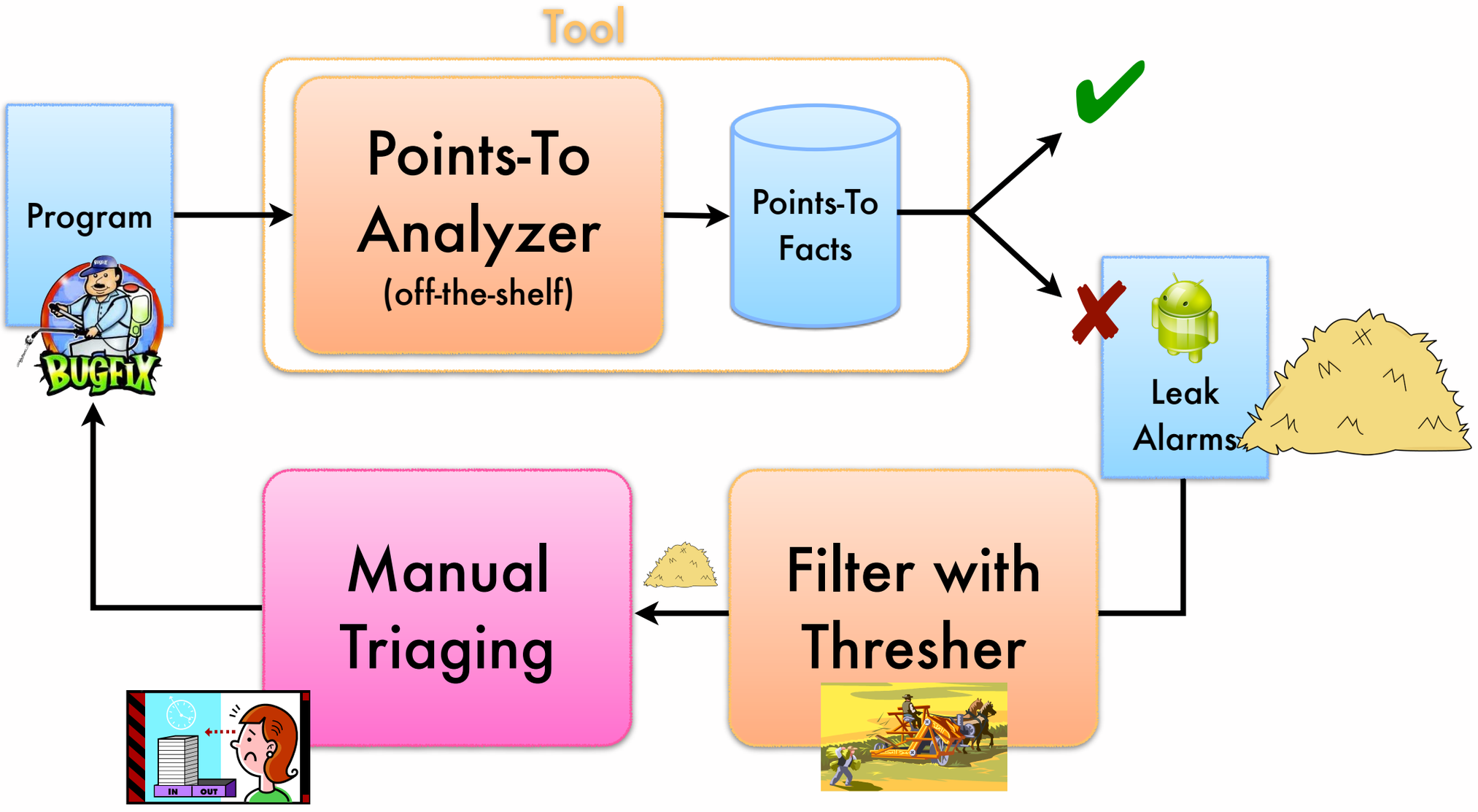

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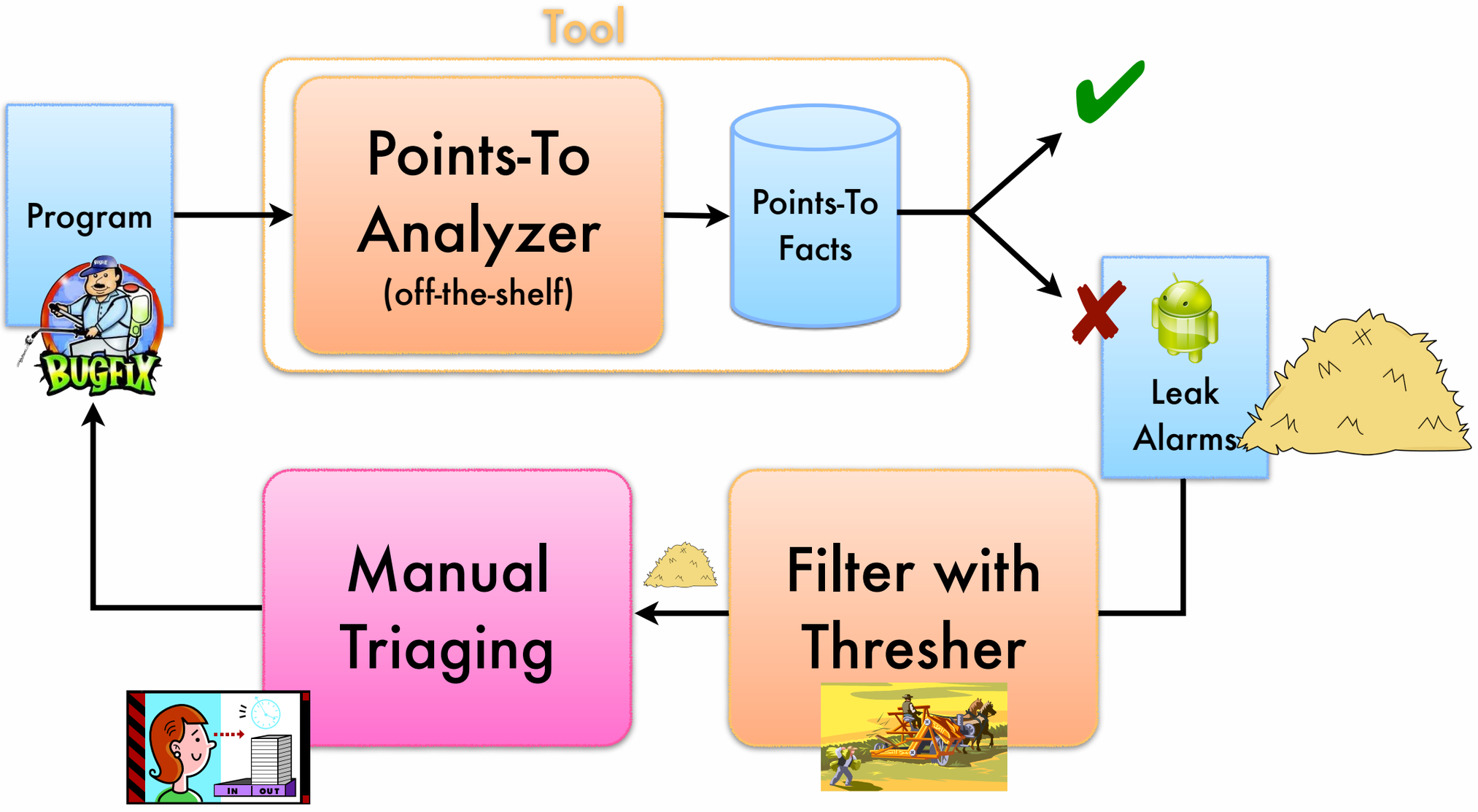

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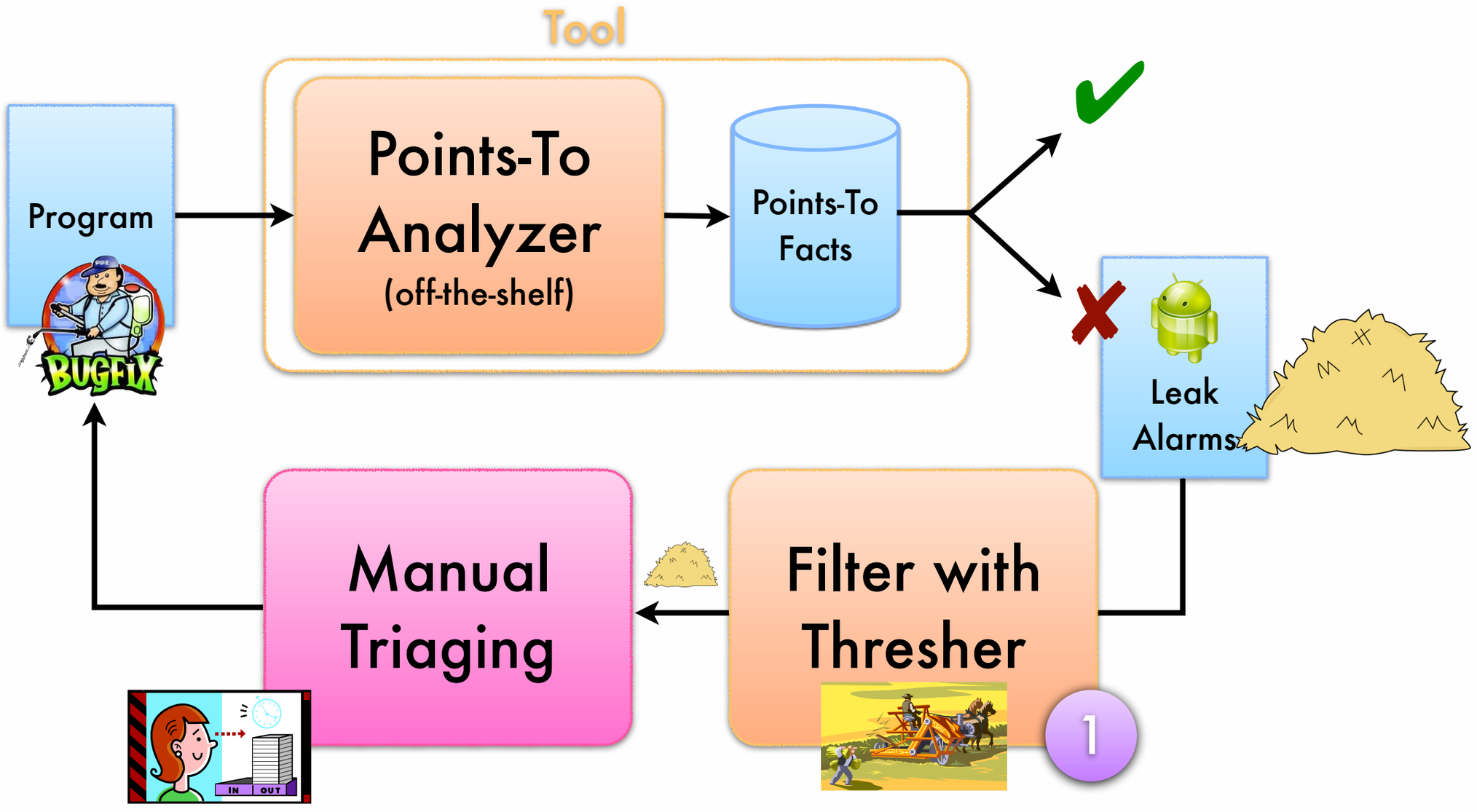
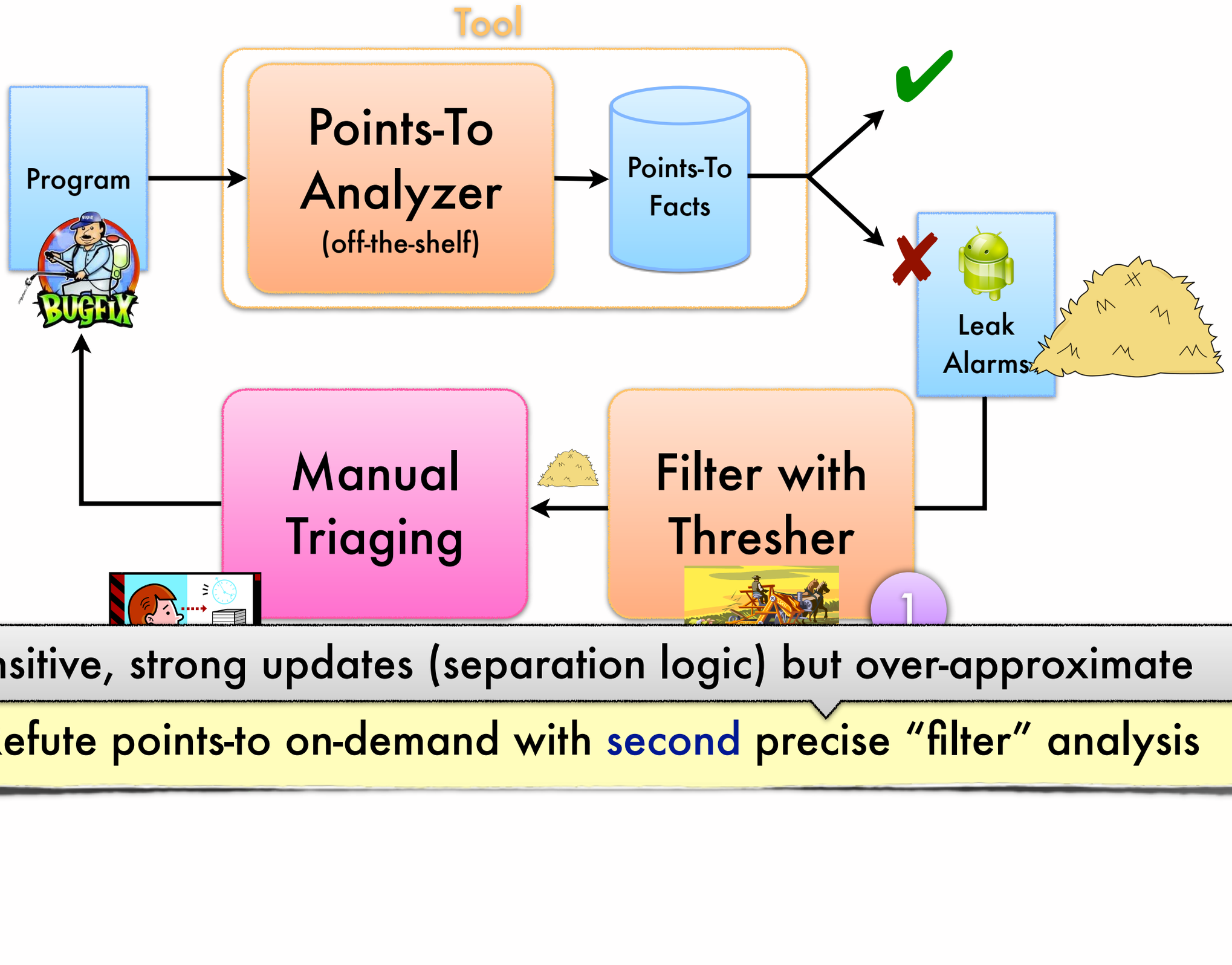


Idea 1: Refute points-to on-demand with second precise "filter" analysis

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



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

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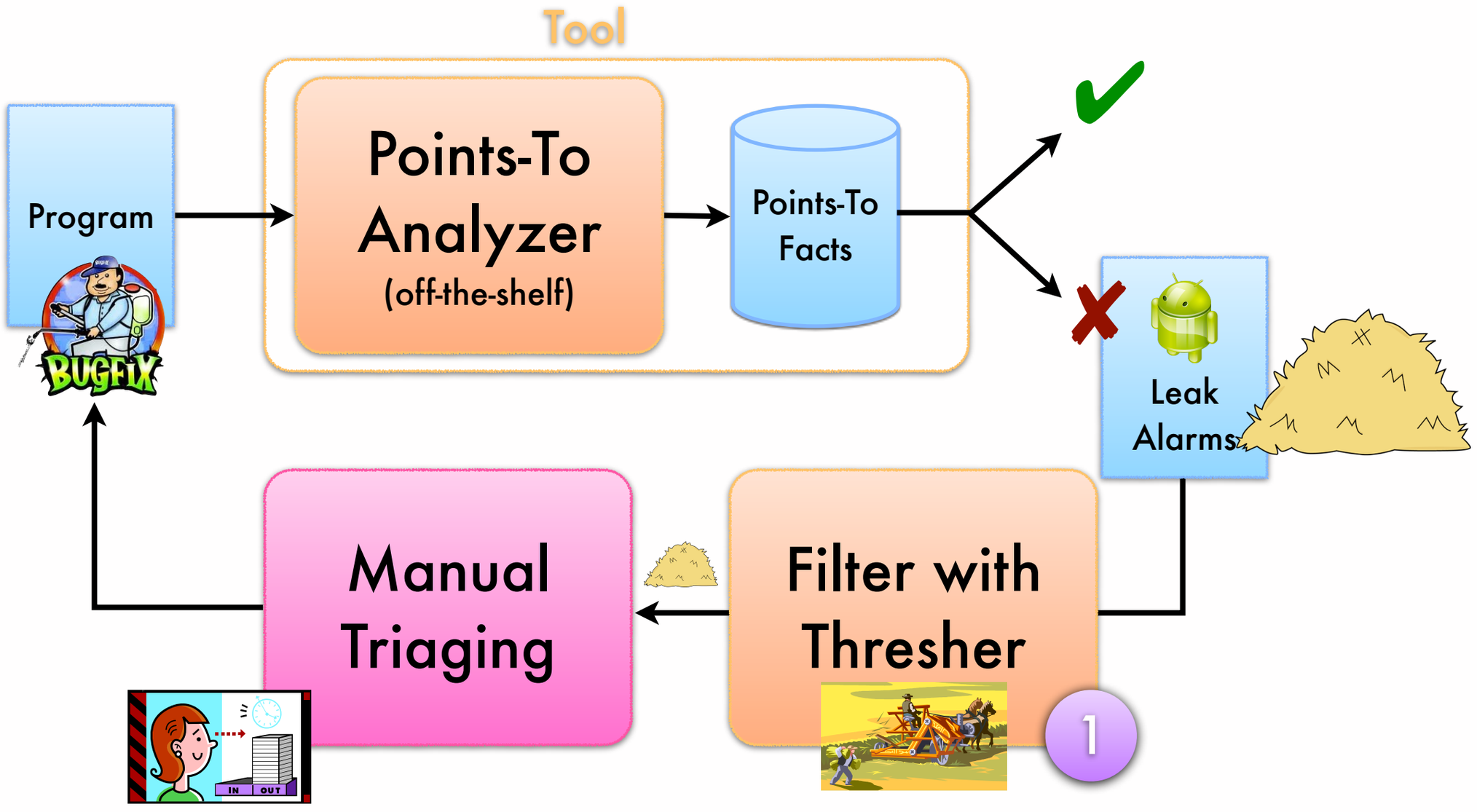

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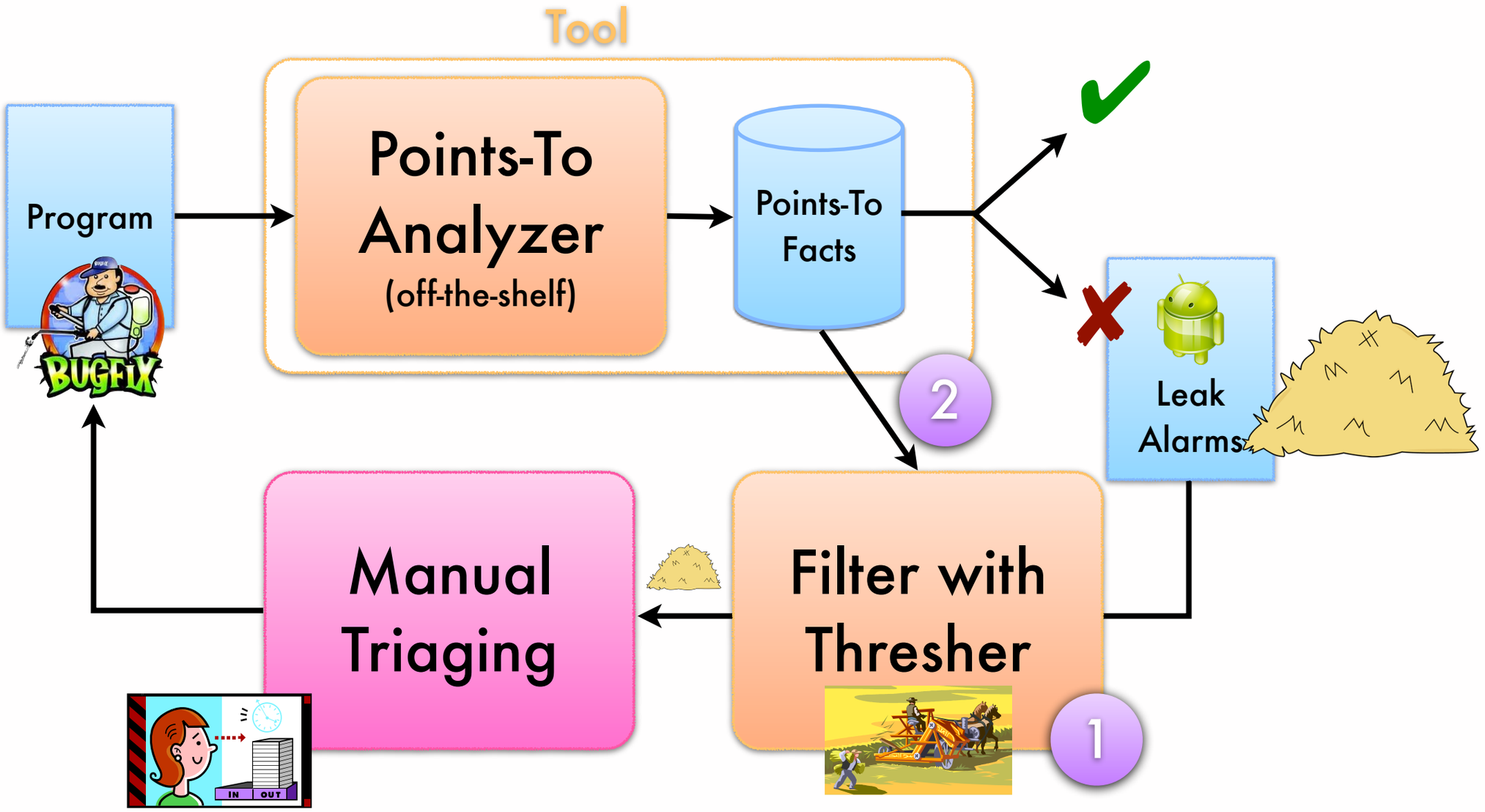
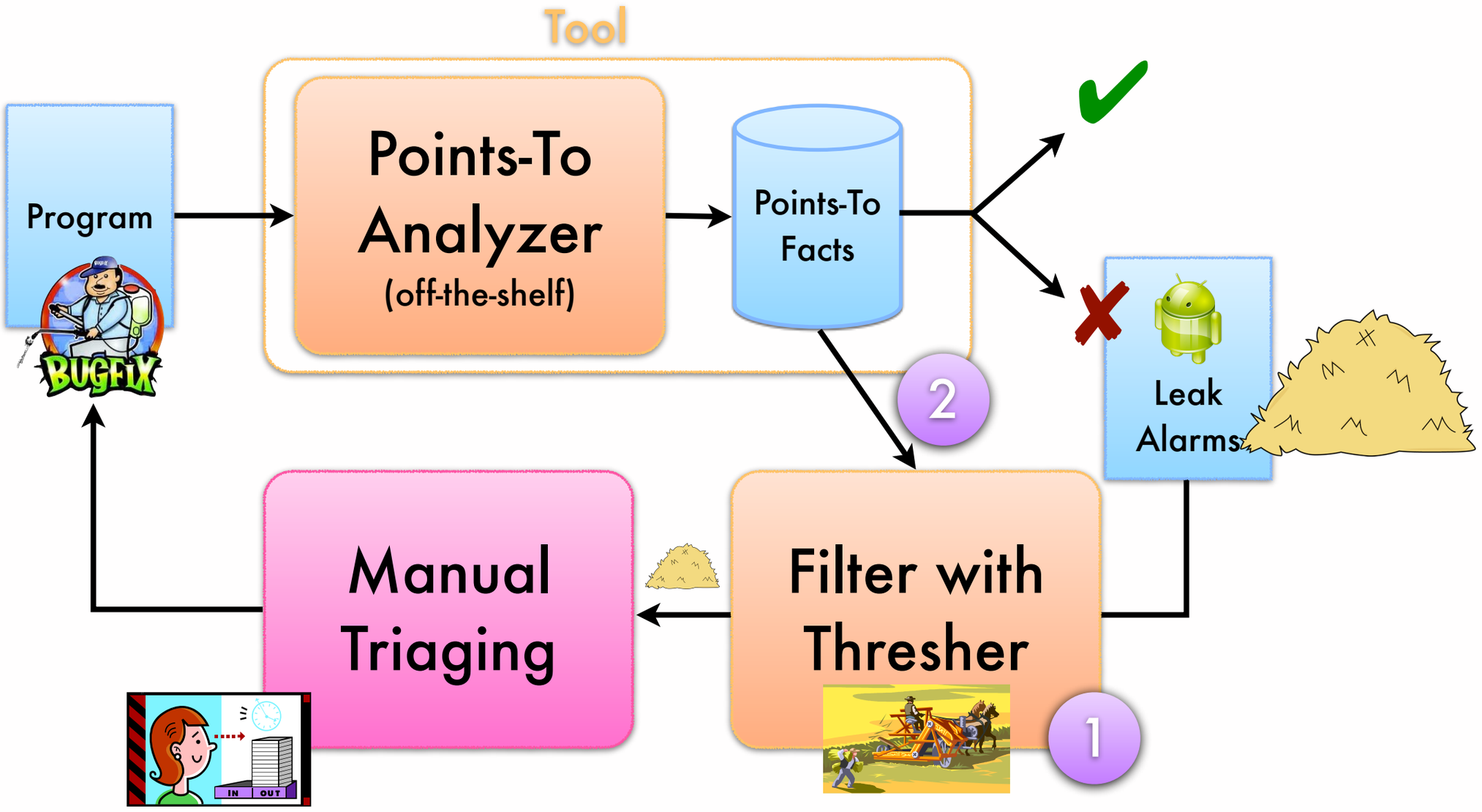


Idea 1: Refute points-to on-demand with second precise "filter" analysis

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.

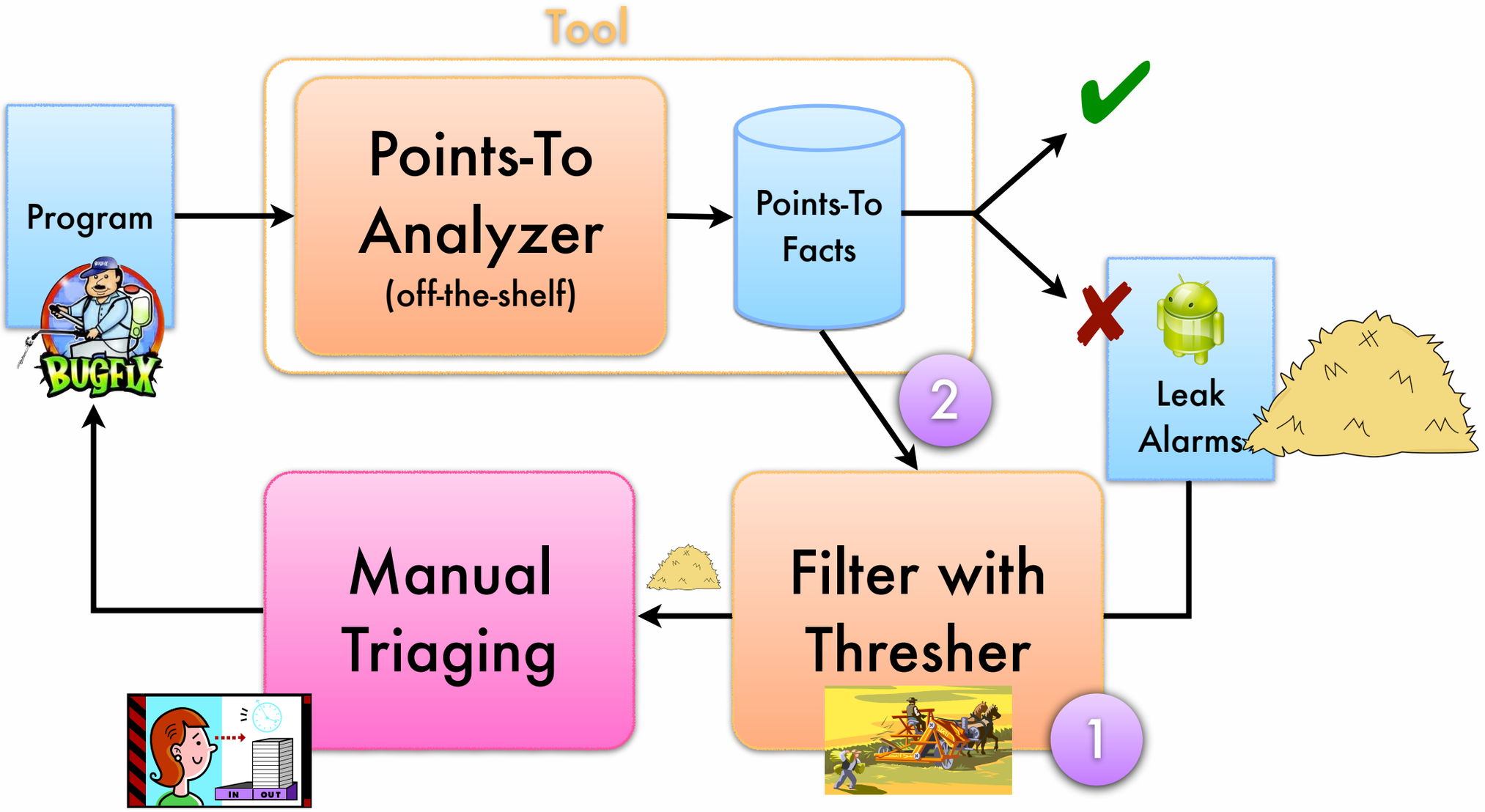


Idea 1: Refute points-to on-demand with second precise "filter" analysis

"**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.



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

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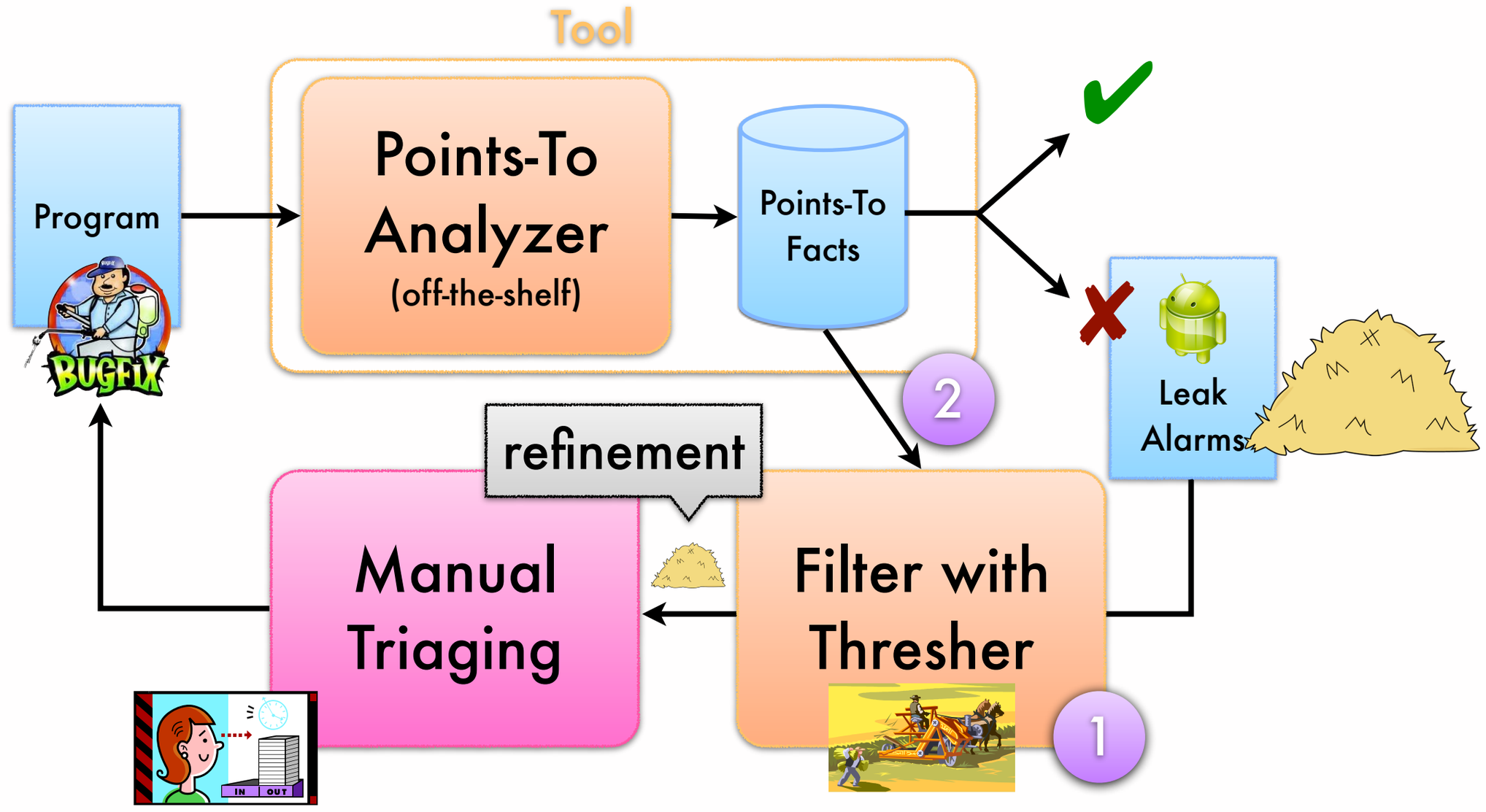

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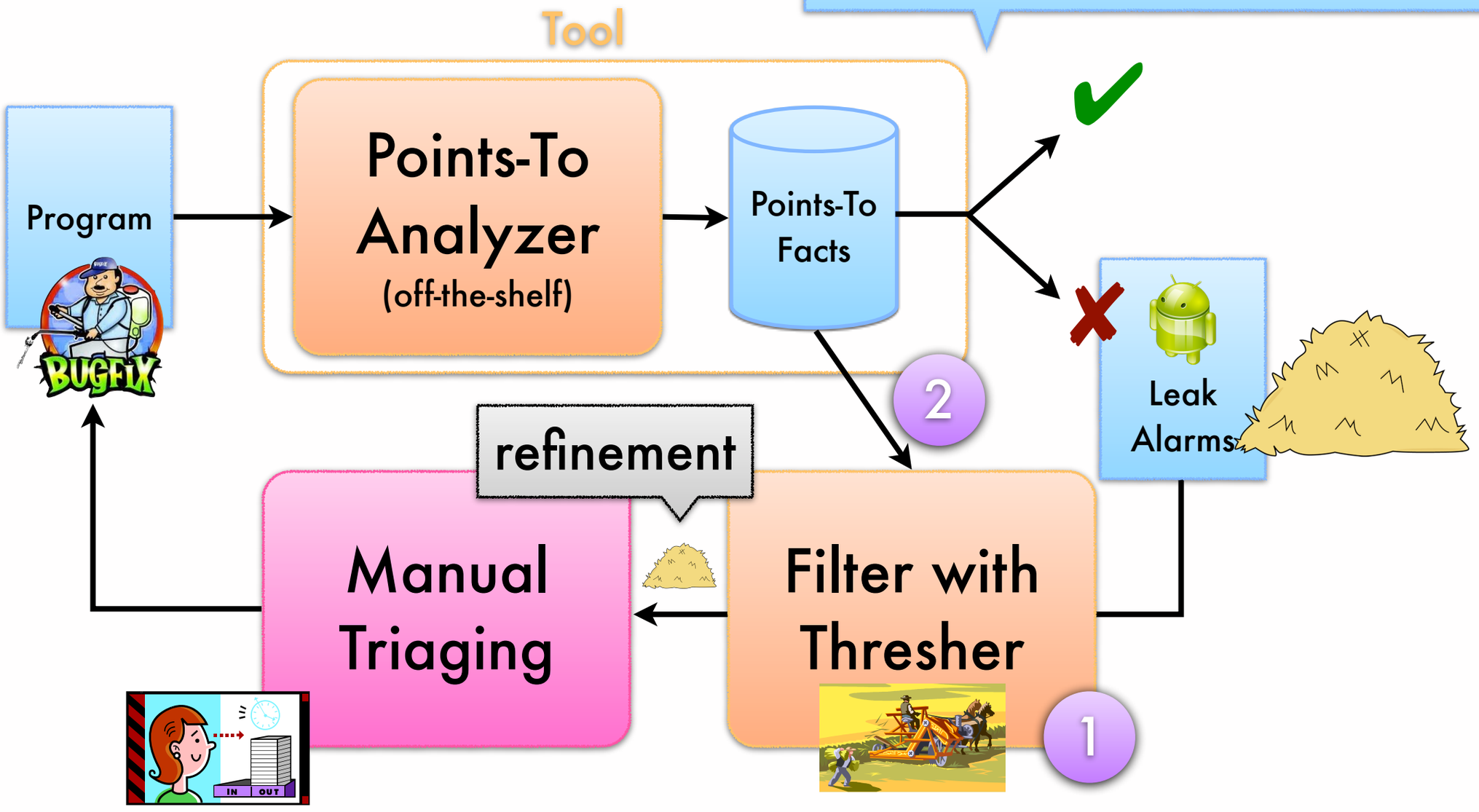
Related: Staged analysis
[Fink, Yahav, Dor, Ramalingam, Geay (2006)]



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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

Is there a program execution where at some time

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Select a points-to edge in the path

A top-level filter:
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⋮

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Try to refute the edge with a symbolic analysis

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✔ Refuted

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False Alarm
Soundly Filtered

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✔ Refuted → False Alarm Soundly Filtered

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Repeat

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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?


```
class Vec {
  static Object[] EMPTY = new_arr0 Object[1]; ...
  Vec() { this.tbl = EMPTY; capacity initially empty }
}
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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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Null object pattern: Should never be written to

Need interprocedural path-sensitivity

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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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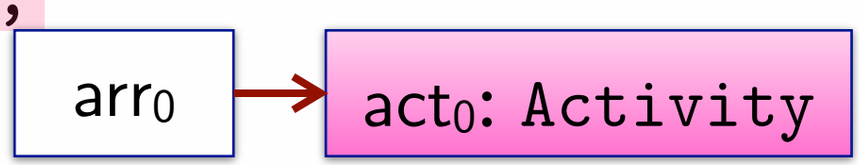

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Derive a contradiction along all "backwards" path programs

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

arr_o·[-] ↦ act_o * true

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

false false false false false false

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Derive refutations by trying to find witnesses

Roadmap: Precise but with scalability challenges

1

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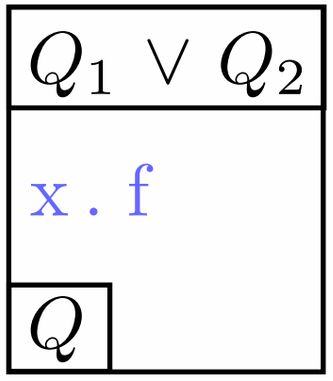
1



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

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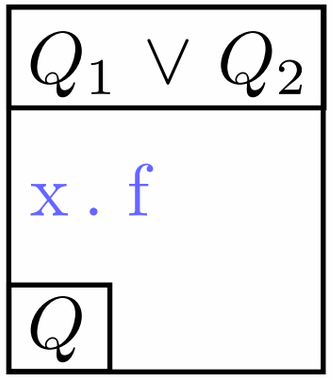

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Roadmap: Precise but with scalability challenges

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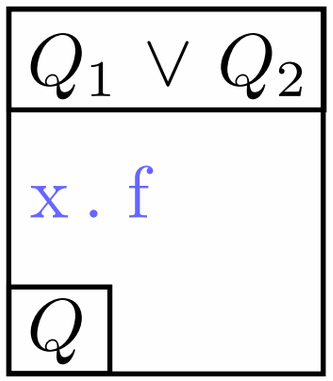

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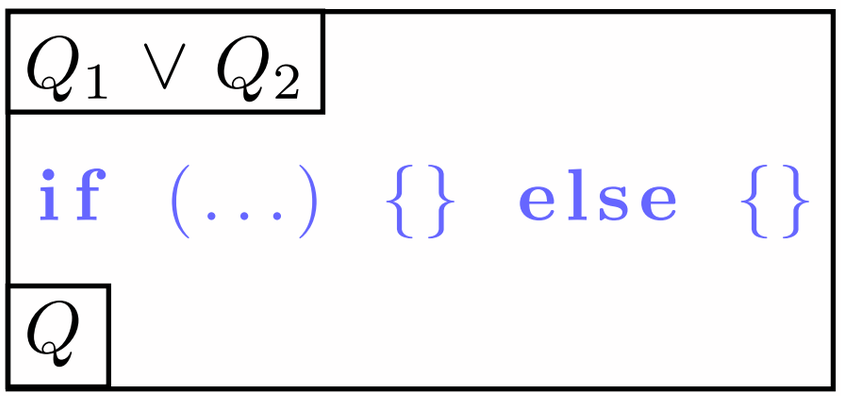

Control-flow path explosion:
Ignore for now, reasonable if number of guards relevant to Q is small (e.g., [Das et al. (2002)])

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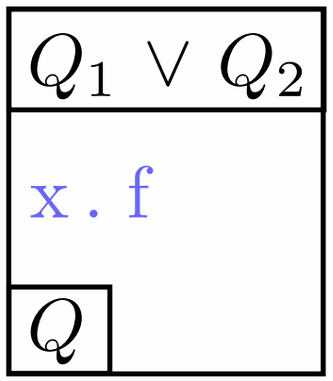

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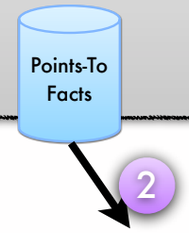

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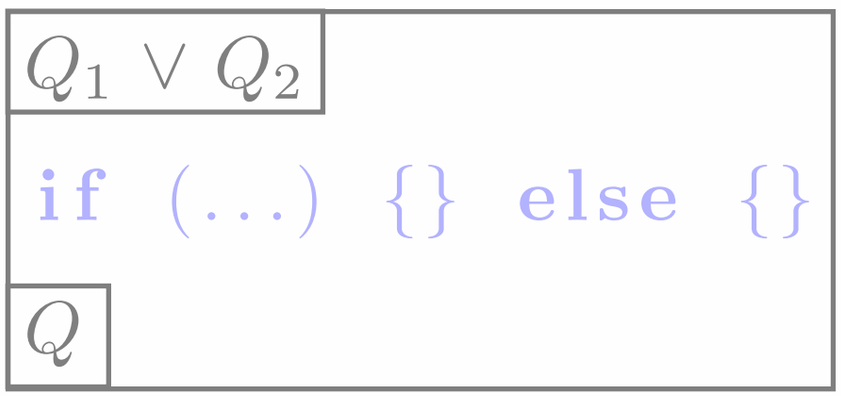

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$Q_1 \vee Q_2$

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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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Points-To Facts

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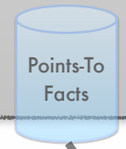

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Over-approximate what?

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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

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"Total" Witness Soundness Criteria

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

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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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Refutation Soundness Criteria

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

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

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

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

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)

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while Q_{inv} $(\ldots)$ {}

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

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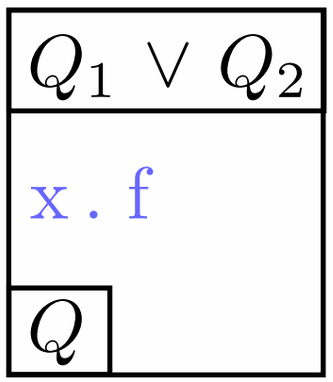

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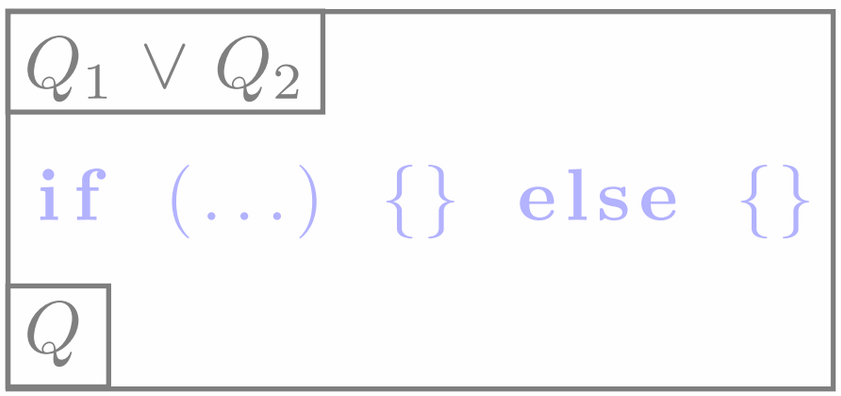

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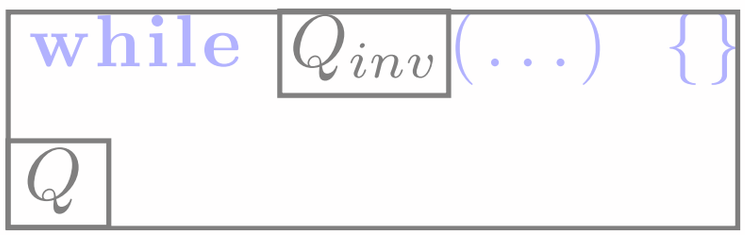

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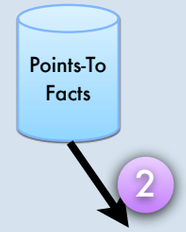

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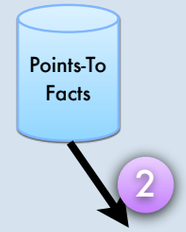

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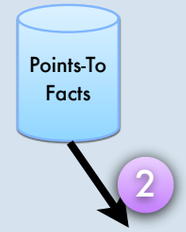

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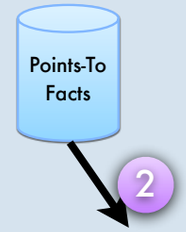

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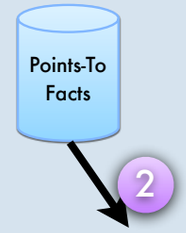

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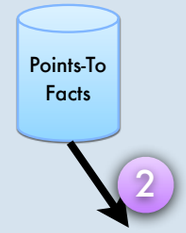

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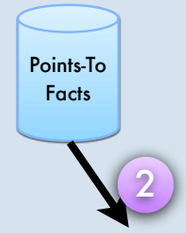

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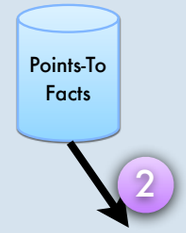

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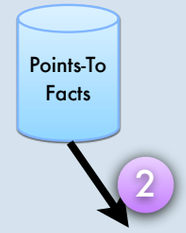

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$\boxed{\mathtt{y \cdot f \mapsto p}}$

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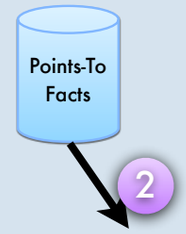

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$\boxed{\mathtt{y} \text{ from } \mathrm{pt}(\mathtt{x}) \cap \mathrm{pt}(\mathtt{y}) \wedge \mathtt{x} = \mathtt{y}}$

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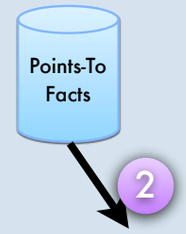

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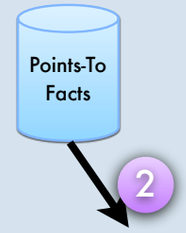

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Generalized disalias check:
$\mathrm{pt}(\mathrm{x}) \cap \mathrm{pt}(\mathrm{y}) = \varnothing$

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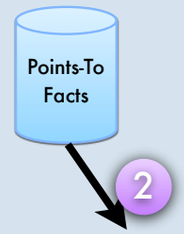

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Restriction on possible abstract locations based on flow in the backwards analysis

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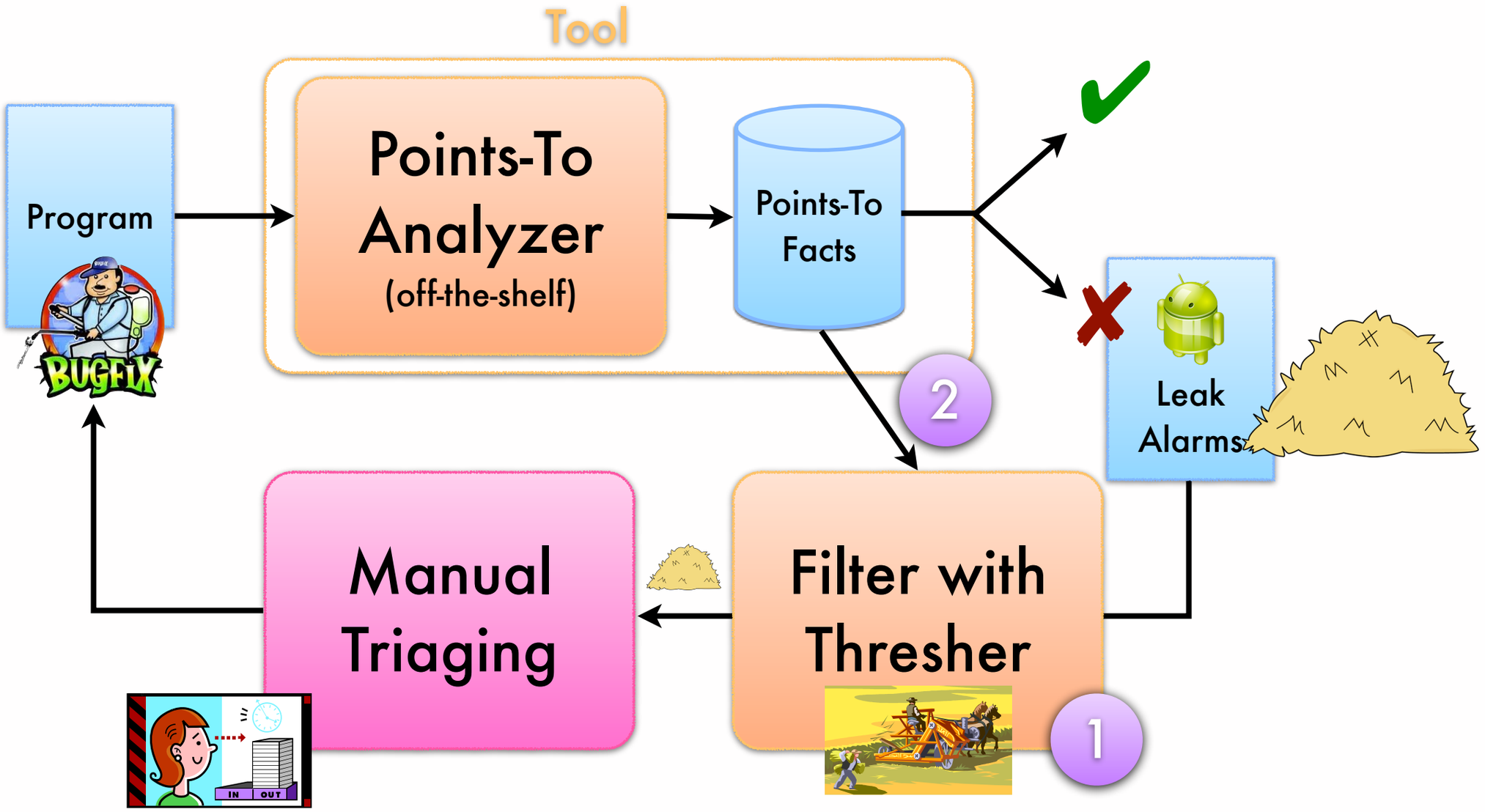
Roadmap: Thresher filters out false alarms by refuting them one-by-one.



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?

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	Thresher Refuted	True Bugs	Thresher Time (s)	False Alarm %	Filtered %
PulsePoint	unknown	16	8	8	95	0	100
StandupTimer	2K	25	15	0	1068	100	60
DroidLife	3K	3	0	3	1	0	-
SMSPopUp	7K	5	1	4	46	0	100
aMetro	20K	54	18	36	18	0	100
K9Mail	40K	208	130	64	374	18	90
Total	**72K**	**311**	**172**	**115**	**1602**	**17**	**88**

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staticfield-Activity pairs

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`staticfield-Activity` pairs

Filtered

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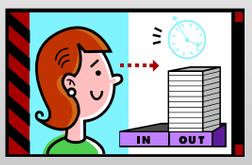
Filtered

Manual



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< ~coffee to lunch break

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% after filtering

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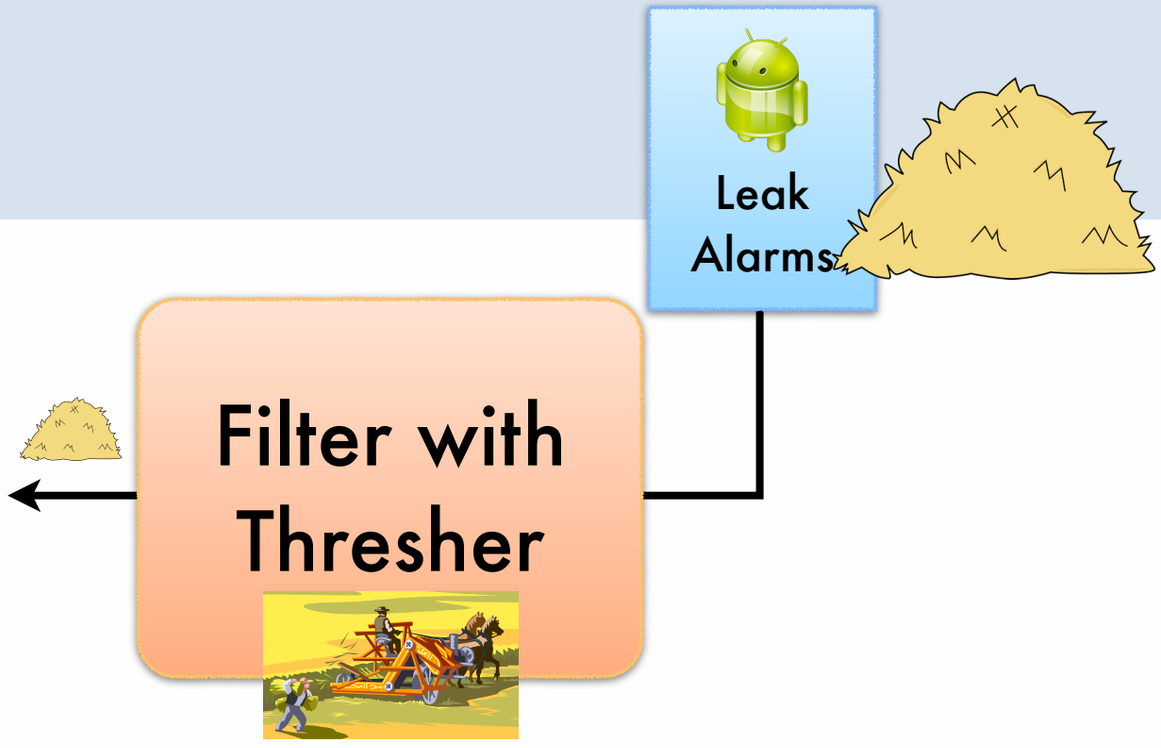
False alarms down to 17% from 63% (points-to analysis only)

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

Roadmap: Precise but with scalability challenges

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Alias path explosion for strong updates
(On write, case split for each possible alias in Q to maintain separation)

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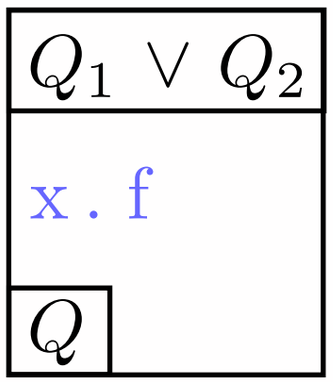

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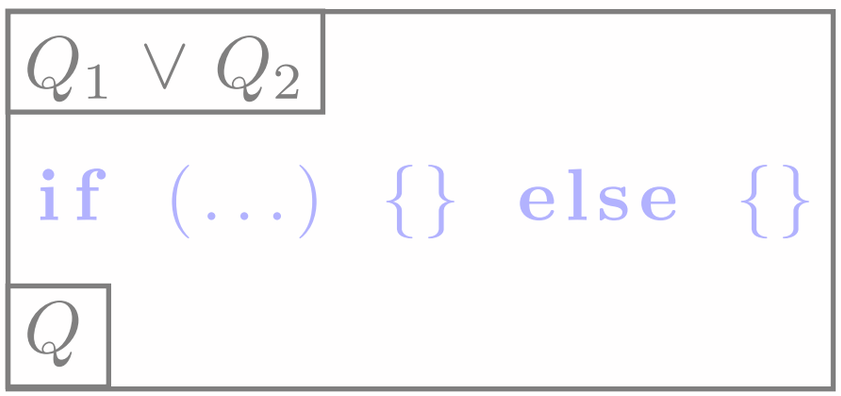

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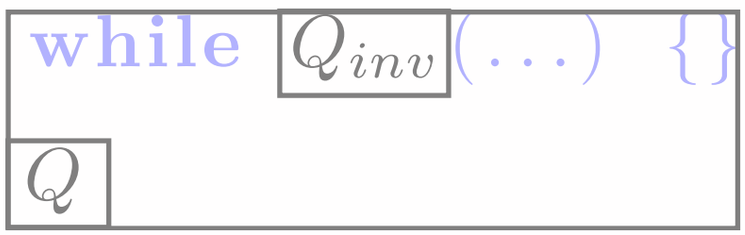

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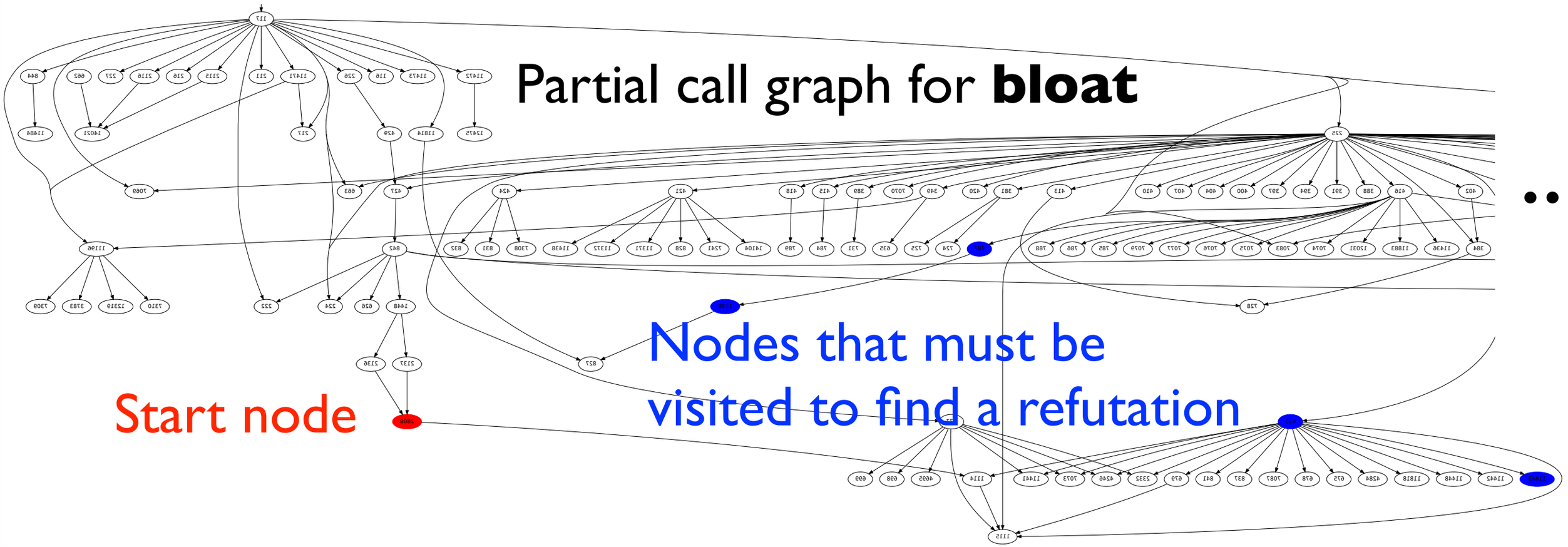
Teaser: Most transitions are irrelevant



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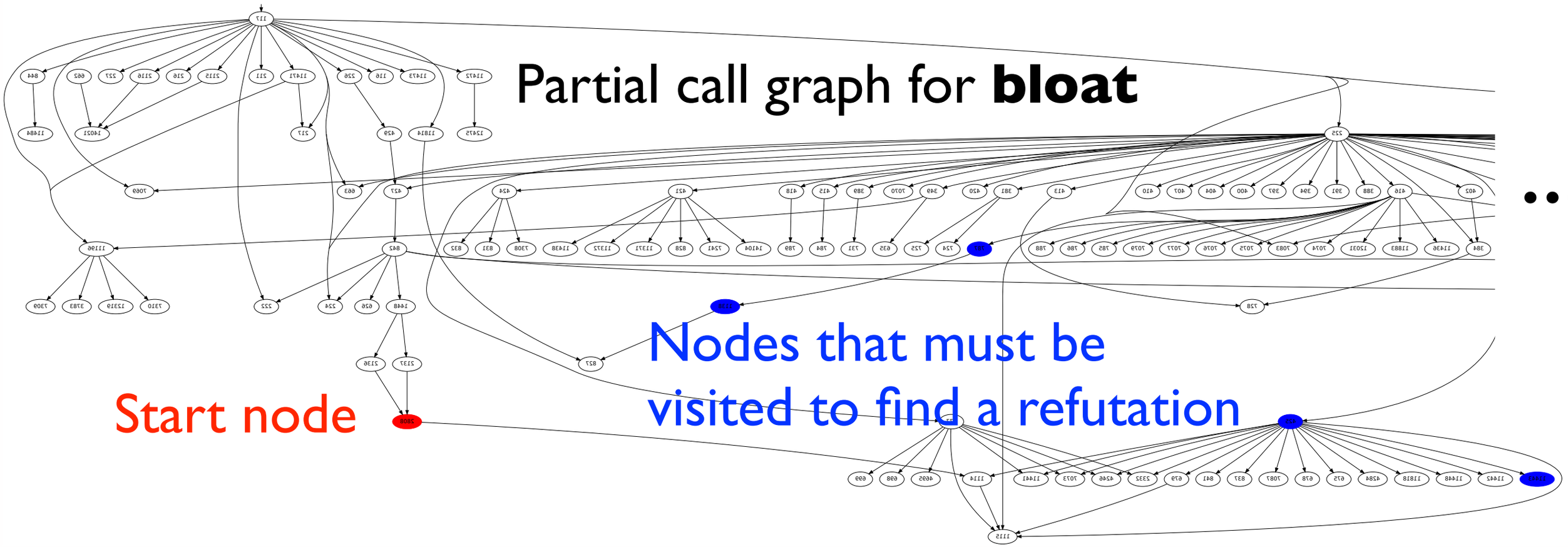
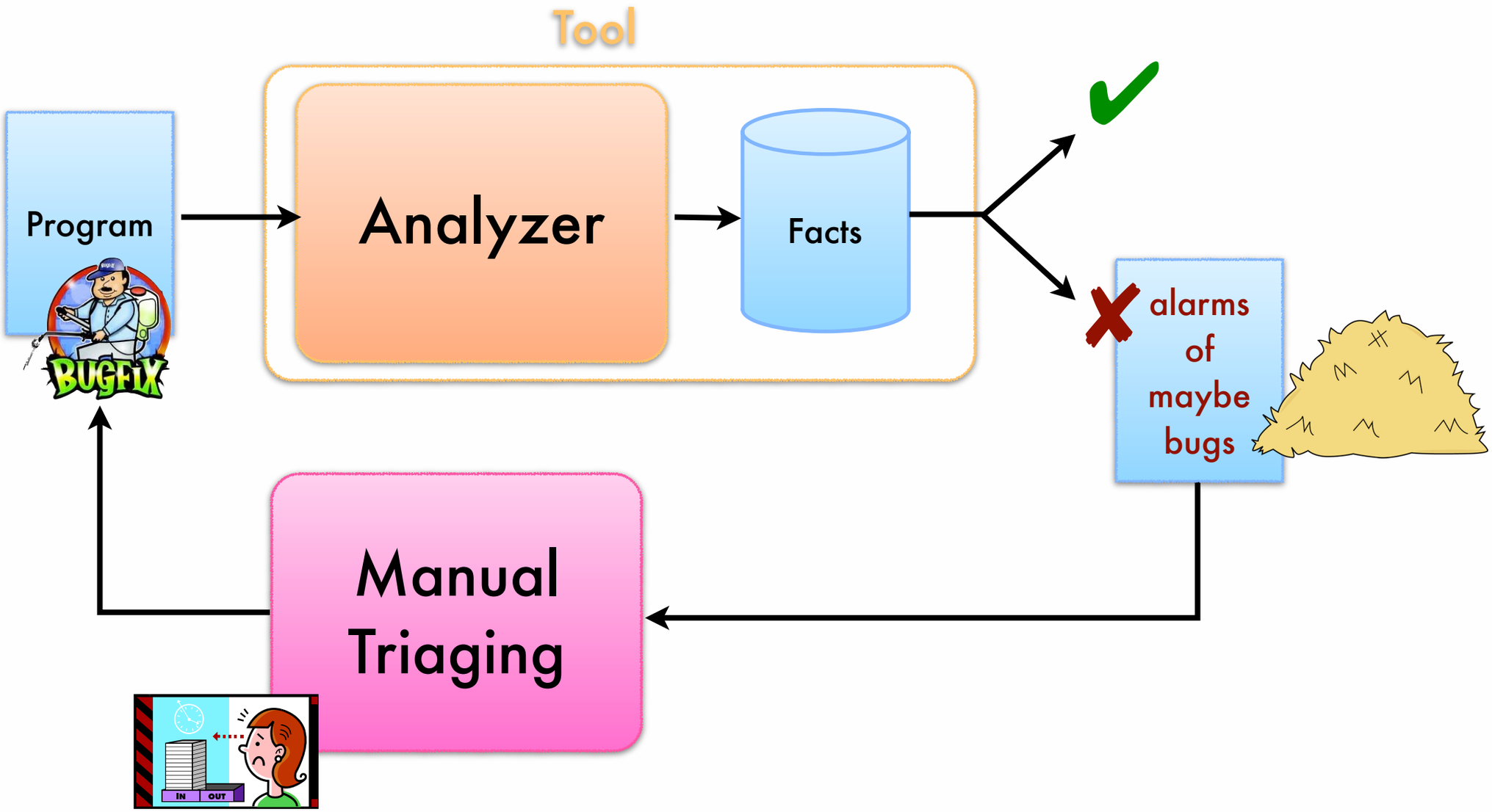


How do we soundly "jump" to the transitions that are **relevant** for deriving the **refutation**?

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



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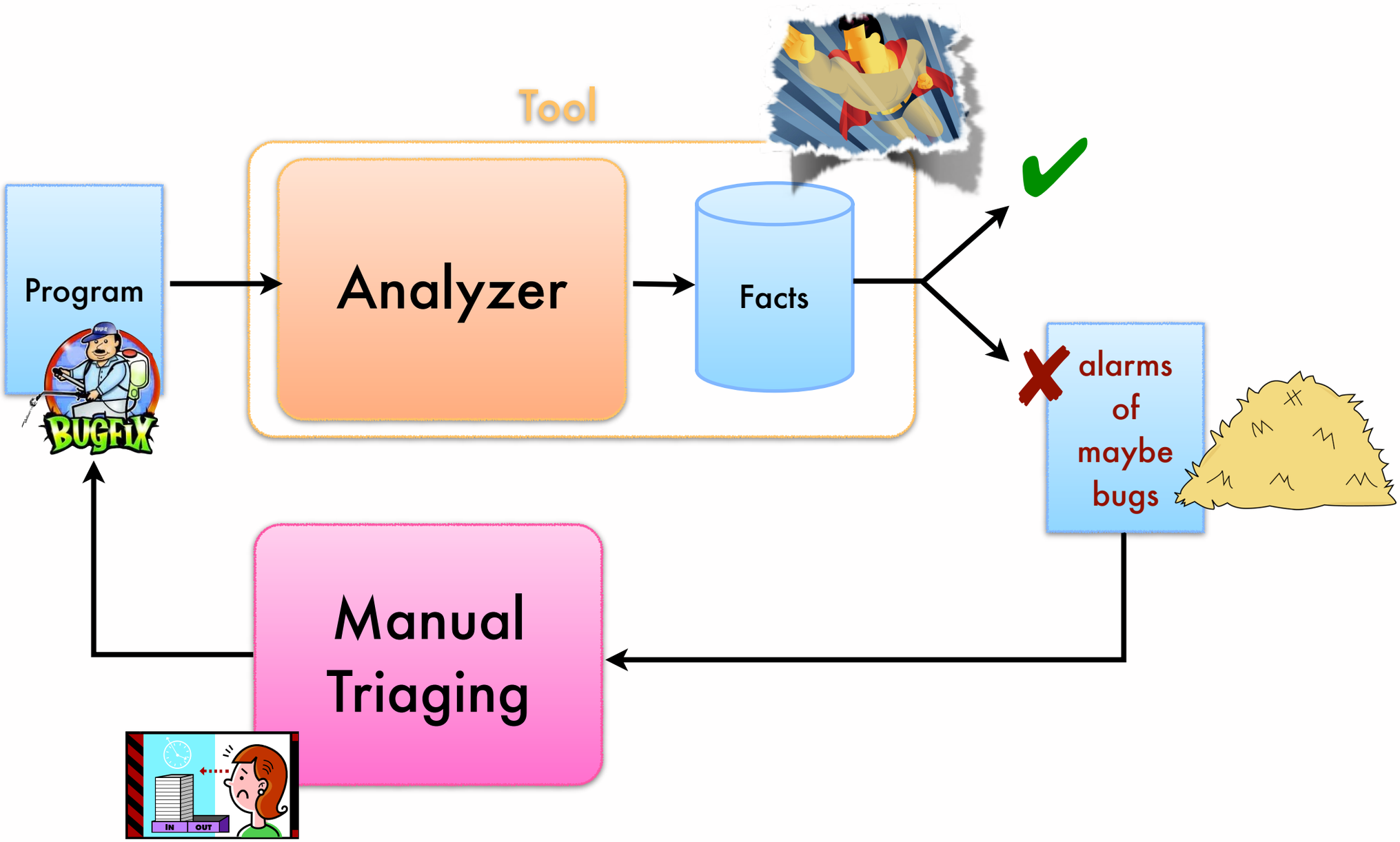

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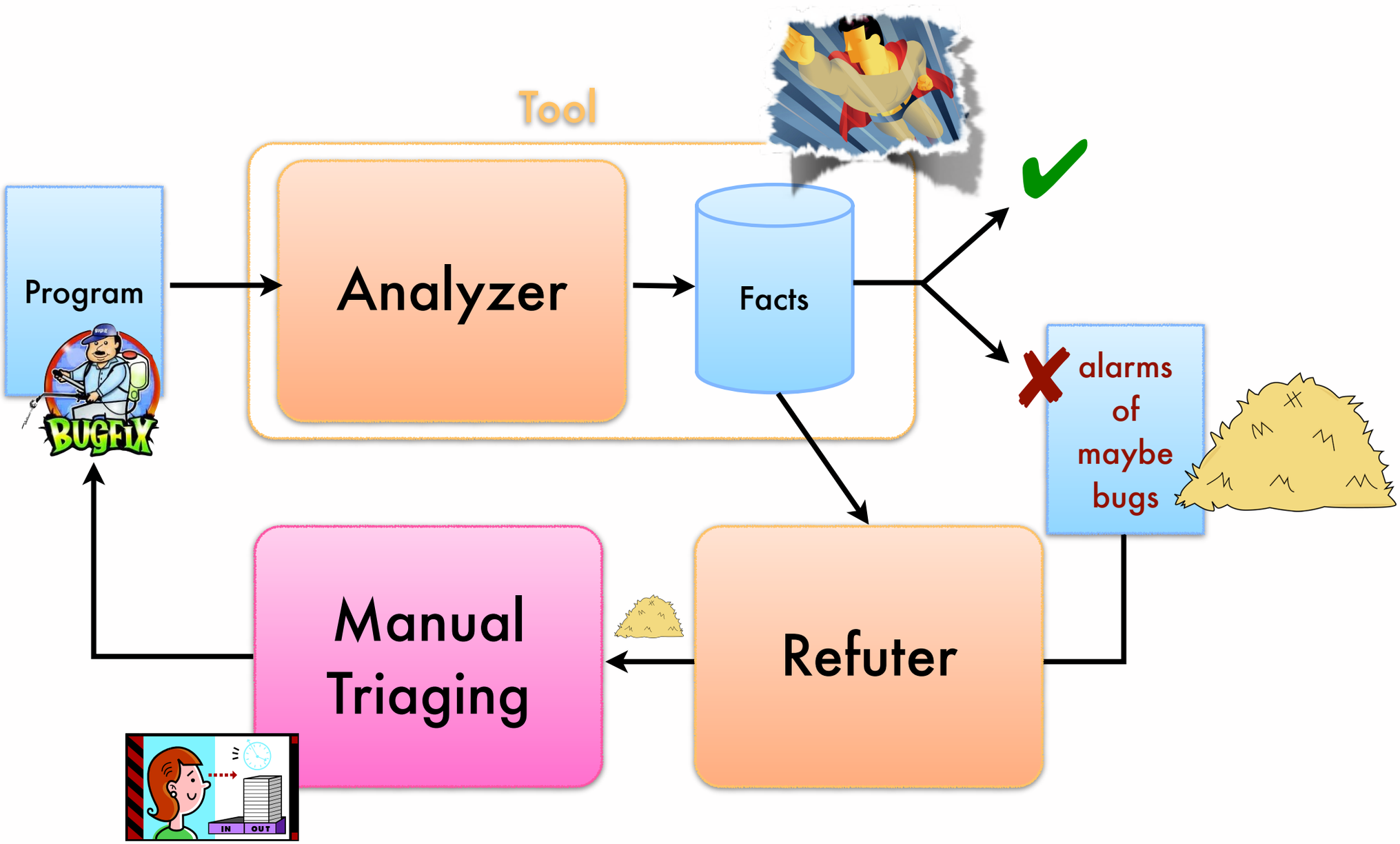

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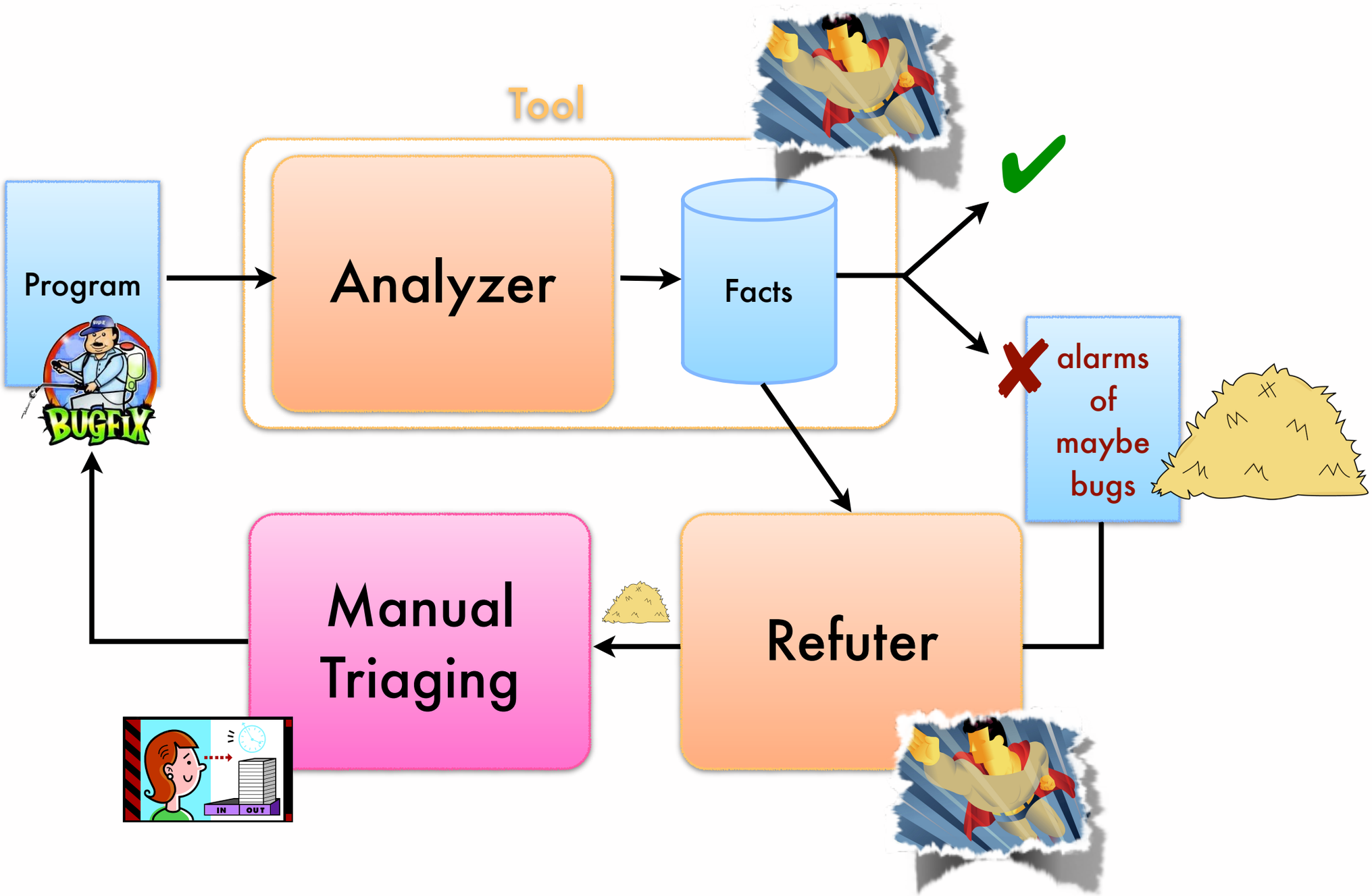

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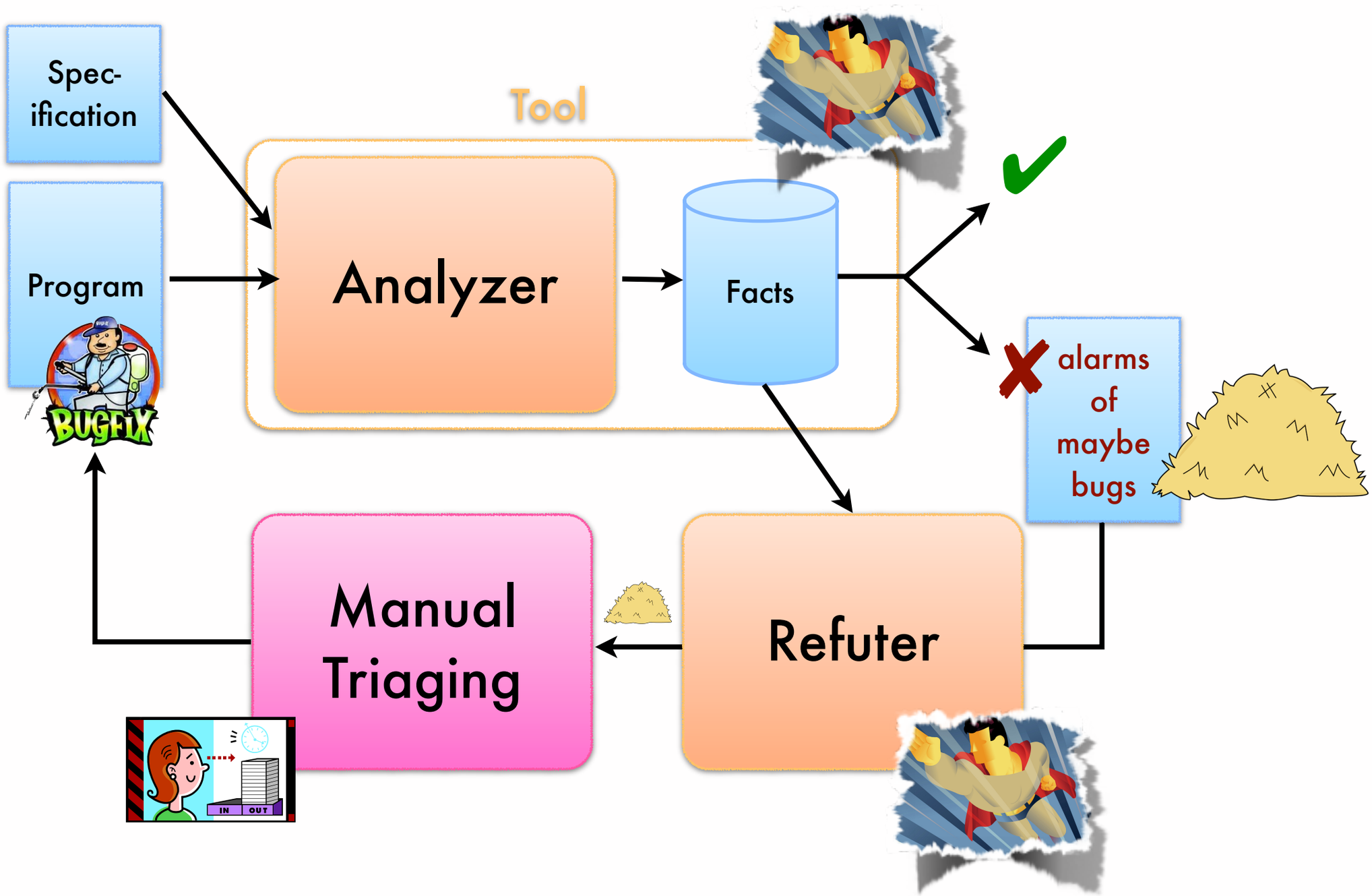

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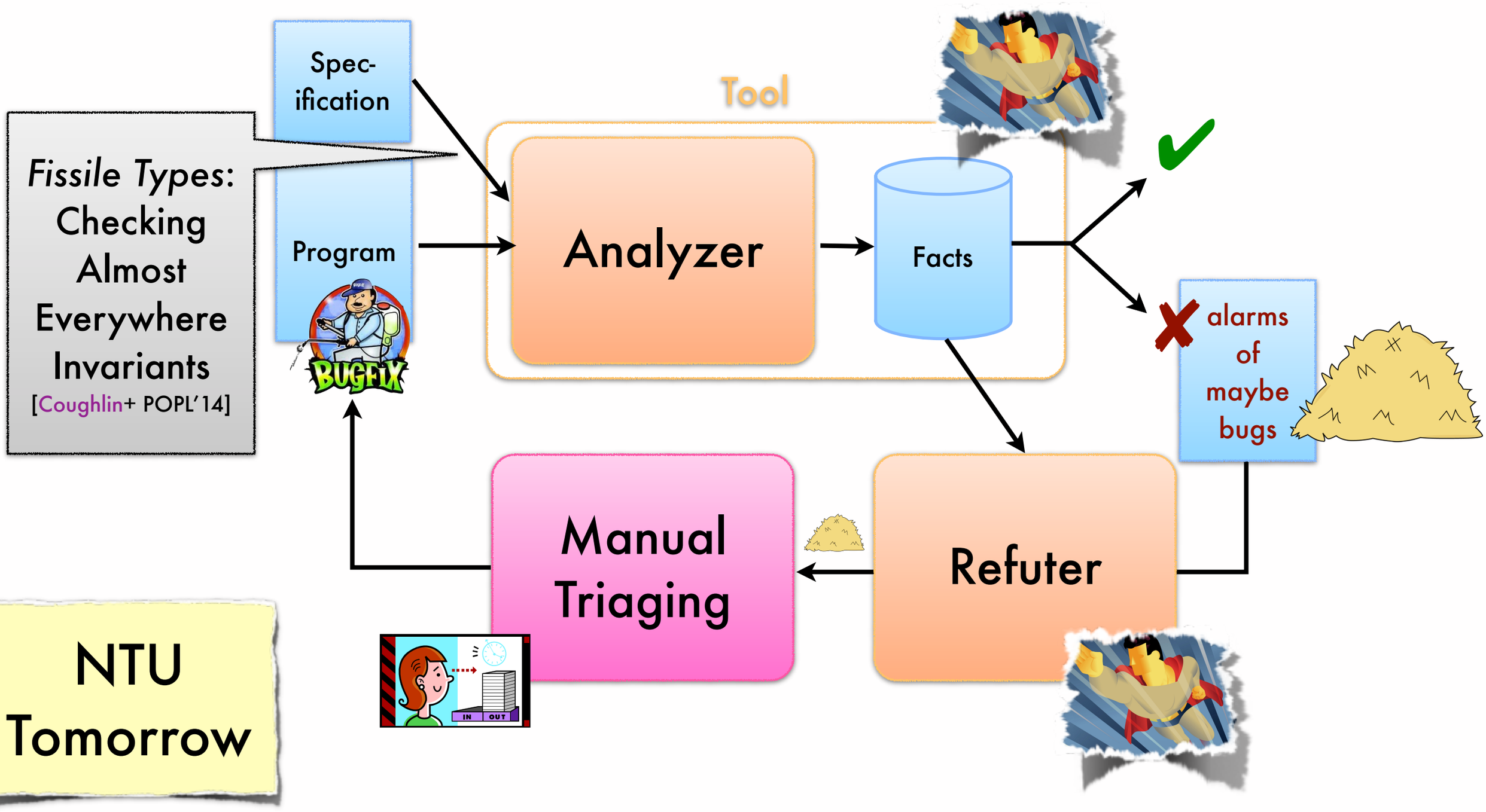

Fissile Types: Checking Almost Everywhere Invariants
[Coughlin+ POPL'14]

NTU Tomorrow

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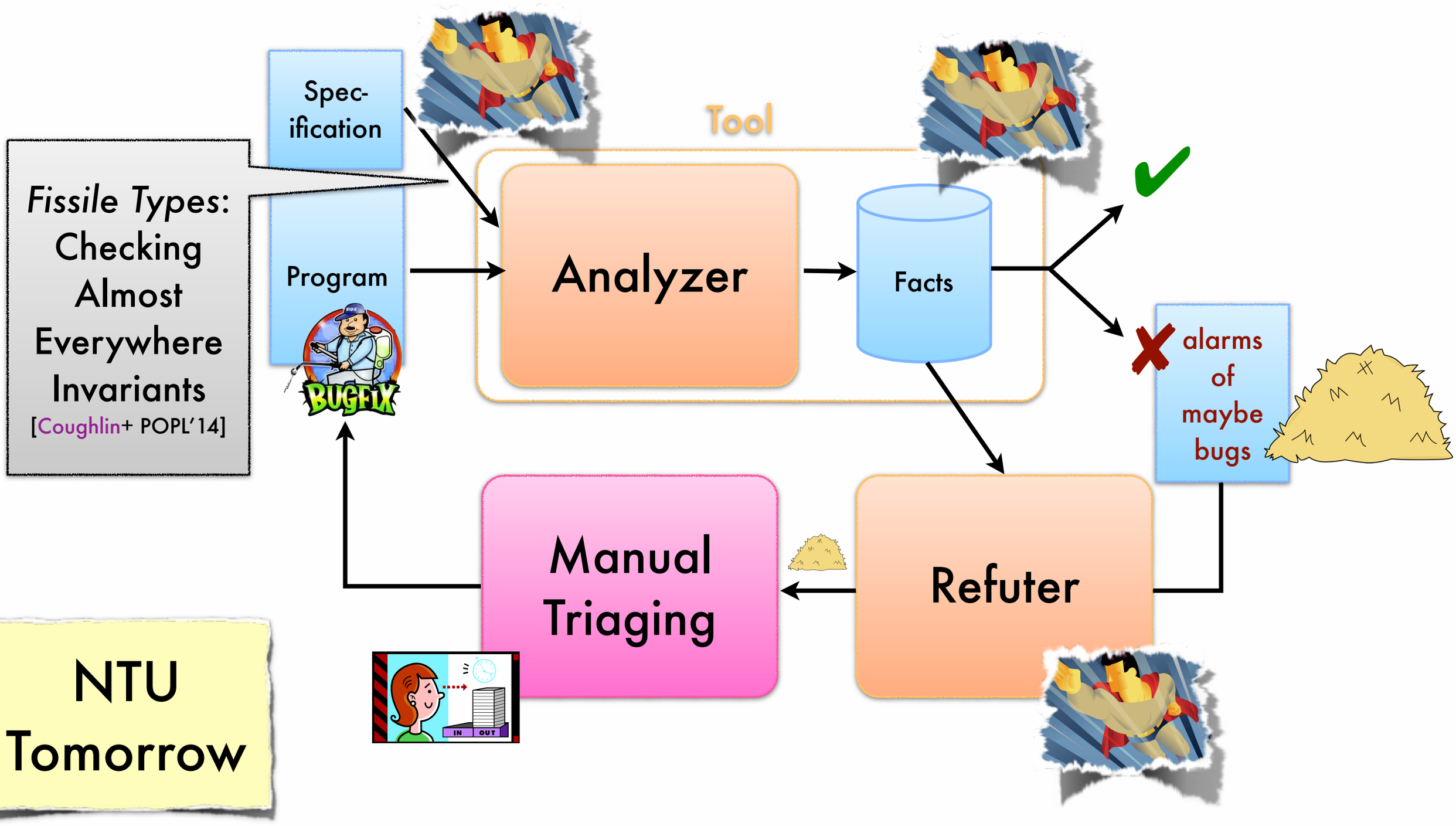

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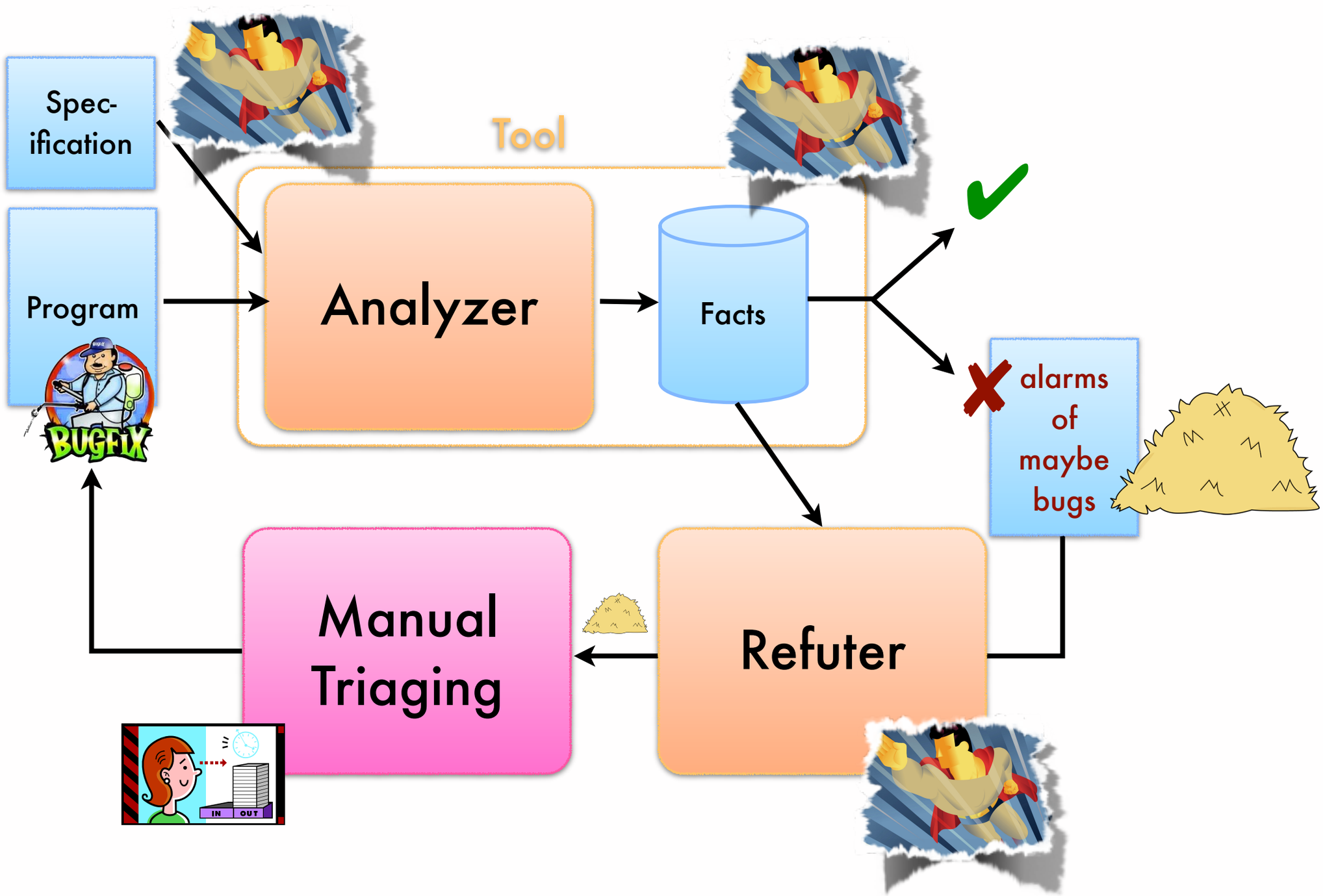

Thank You!

PLV

www.cs.colorado.edu/~bec

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Thank You!

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pl.cs.colorado.edu


Cerny


Chang


Sankaranaryananan


Somenzi

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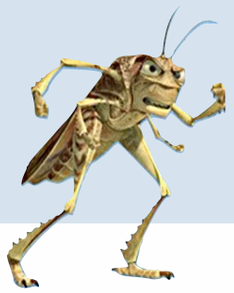

Null object pattern: Should never be written to

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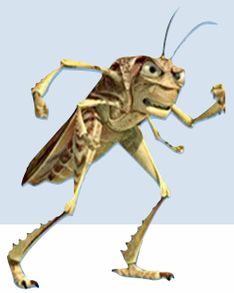

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allocate new backing array on first write

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

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allocate new backing array on first write

return 0

return "evil" content

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    this.
  }
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allocate new backing array on first write

We reported this, Google fixed it

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

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