



# Cooperative Program Analysis


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Colorado State University
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PLV



# A program analysis story ...


A380


Software is everywhere and varying more and more

traditional


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mobile


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cloud


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cyberphysical

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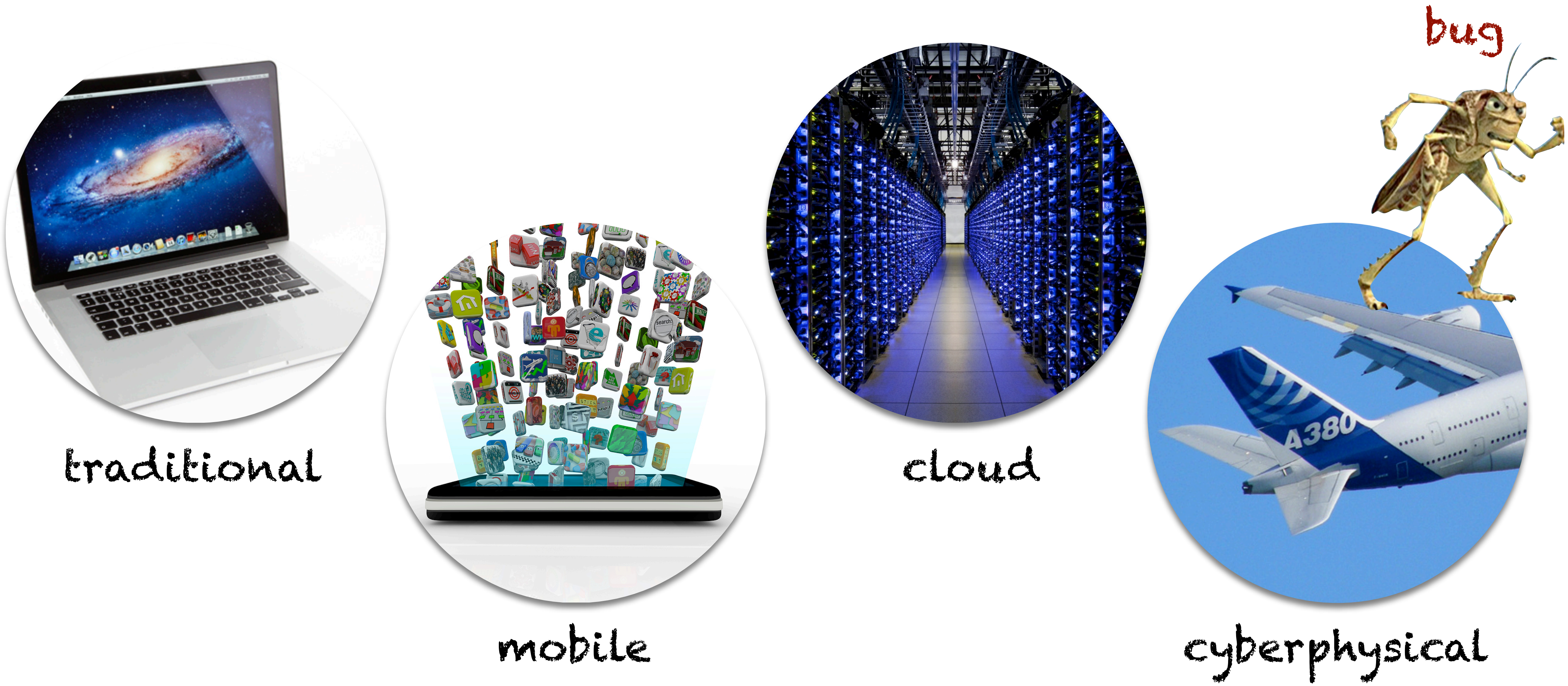


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HELP!

1980s: Bug in Therac-25 kills 6

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2000s: Conficker worm costs $9.1 billion in damages

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Today: "Don't buy this app, it crashes."


Program
Analysis

# How does program analysis save the day?


## Program Analysis for Formal Verification


Systematically examine the program to "simulate" running it on "all inputs"

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The End?

# The Ugly, Hidden Truth


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Undecidability necessitates the possibility of **false alarms**. We hope not too many.

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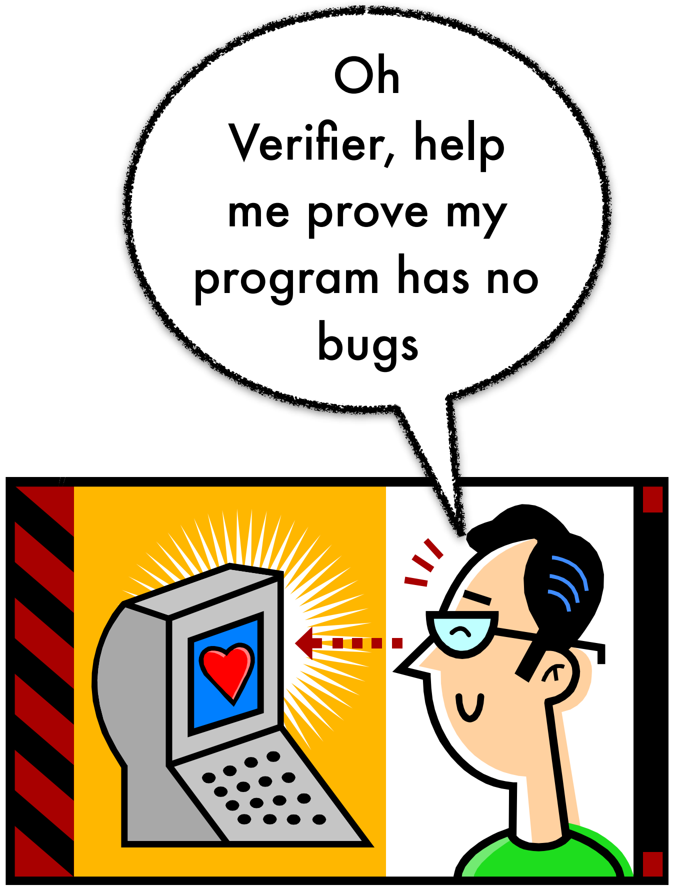

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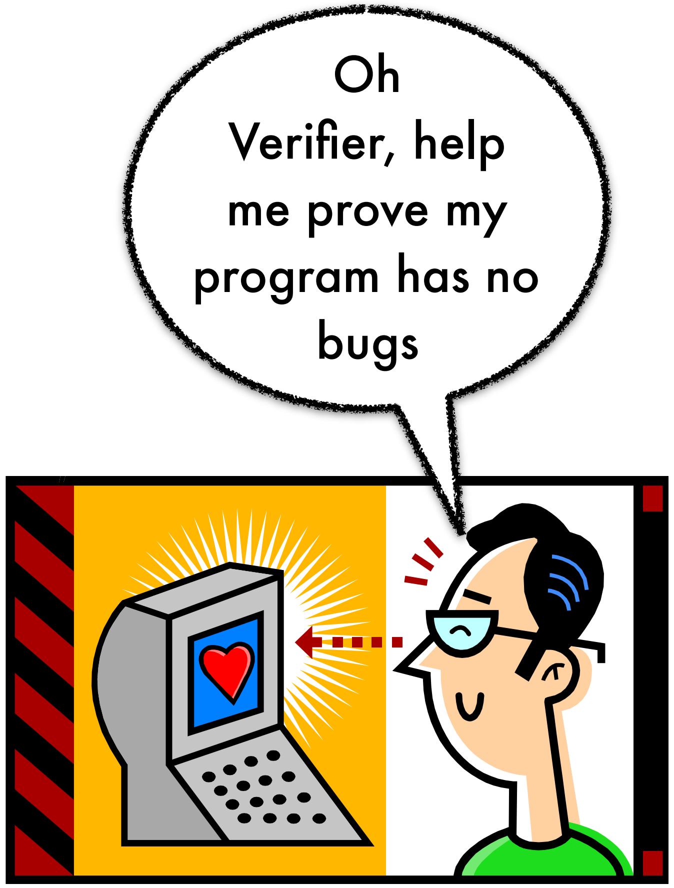


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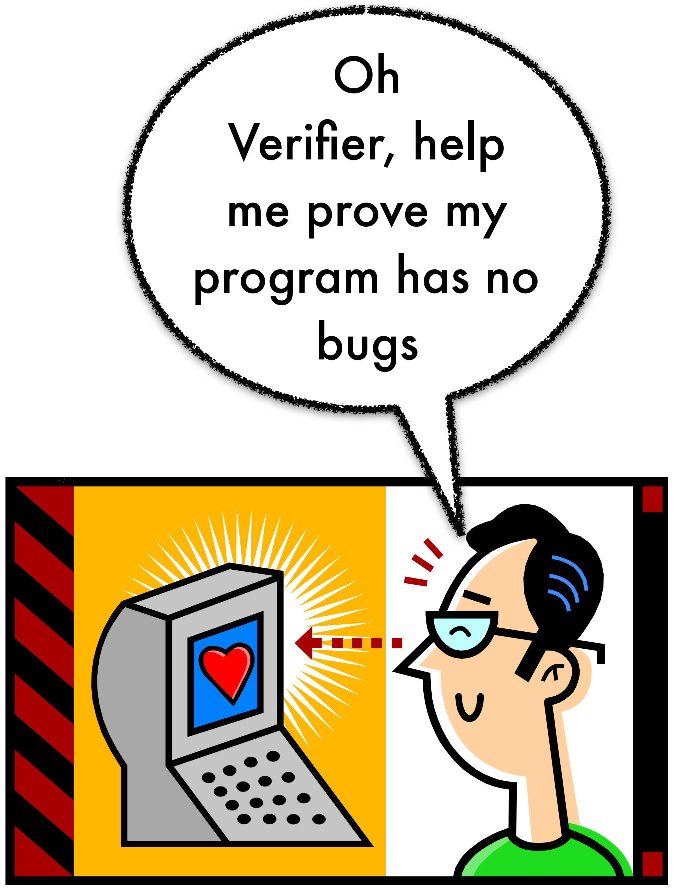


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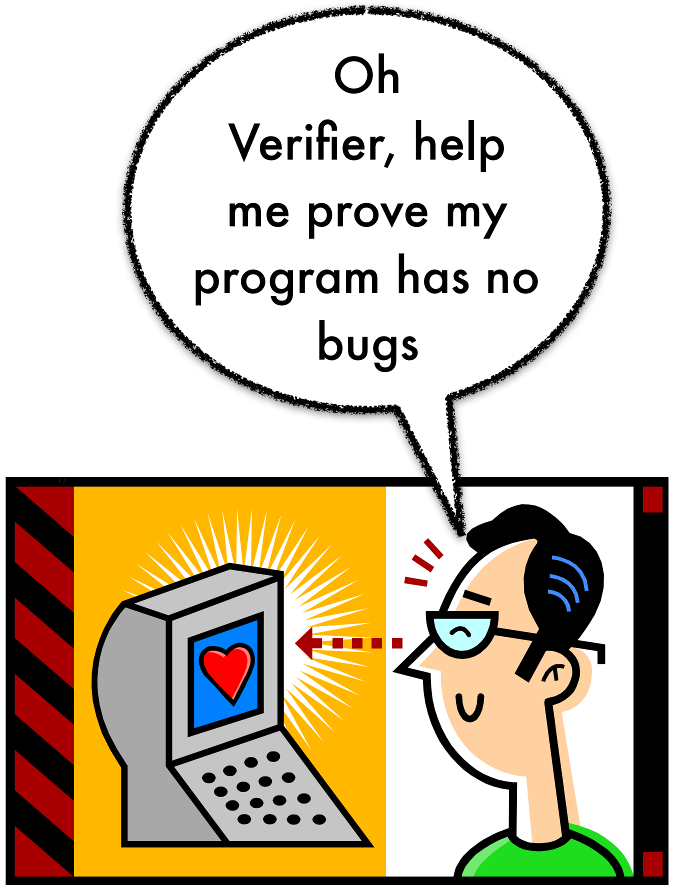


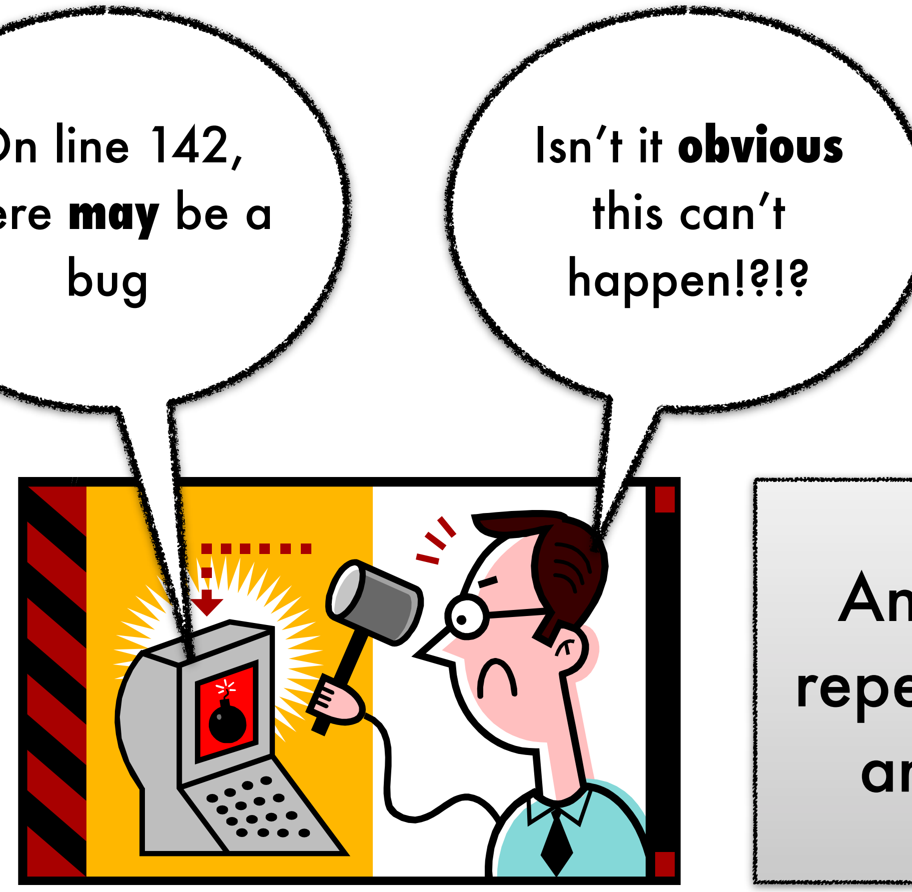


And noisily repeated over and over!

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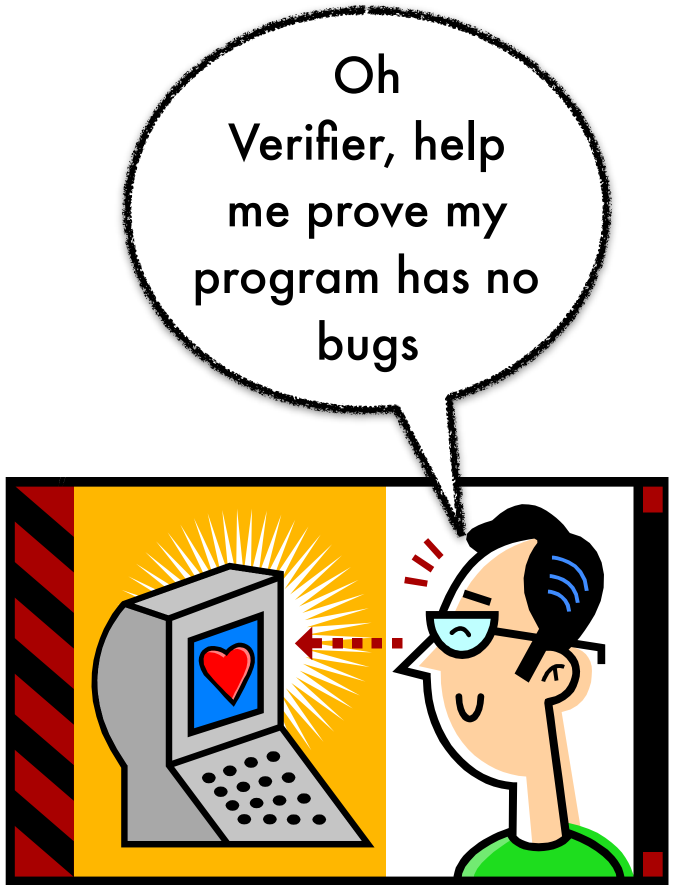


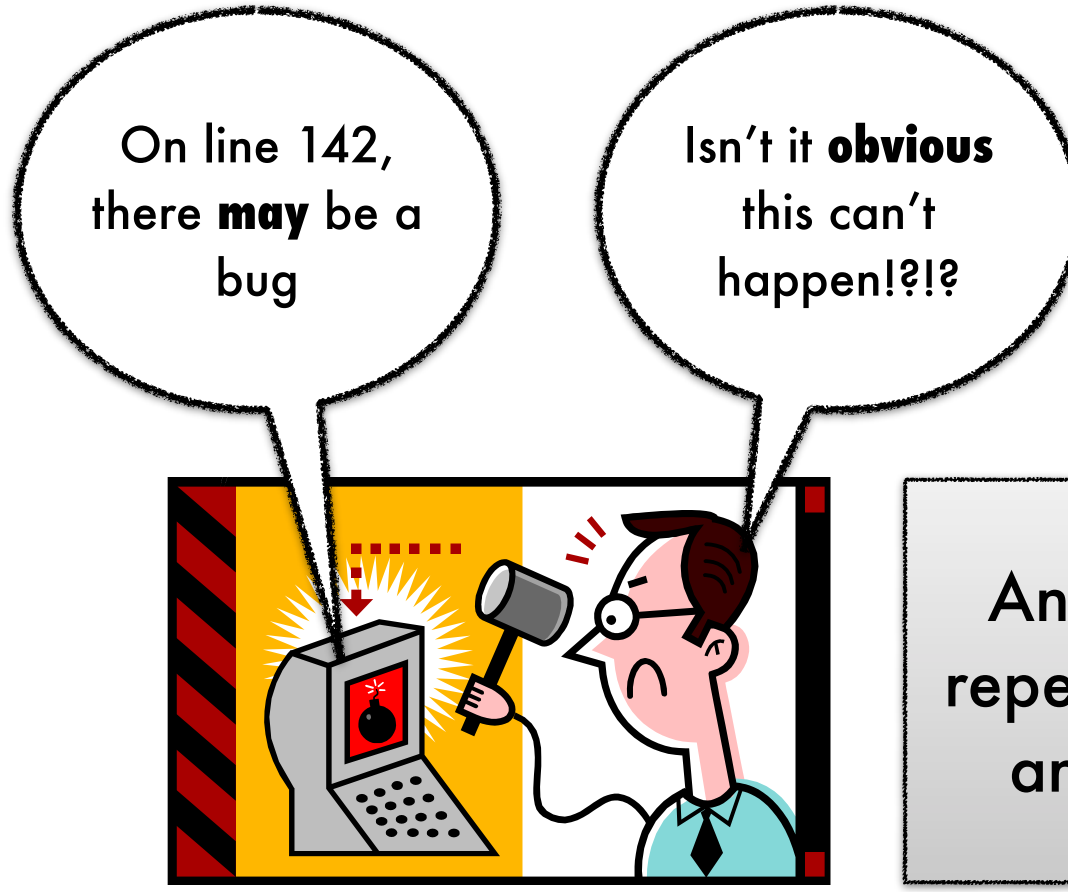


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The well-known **false alarm** problem

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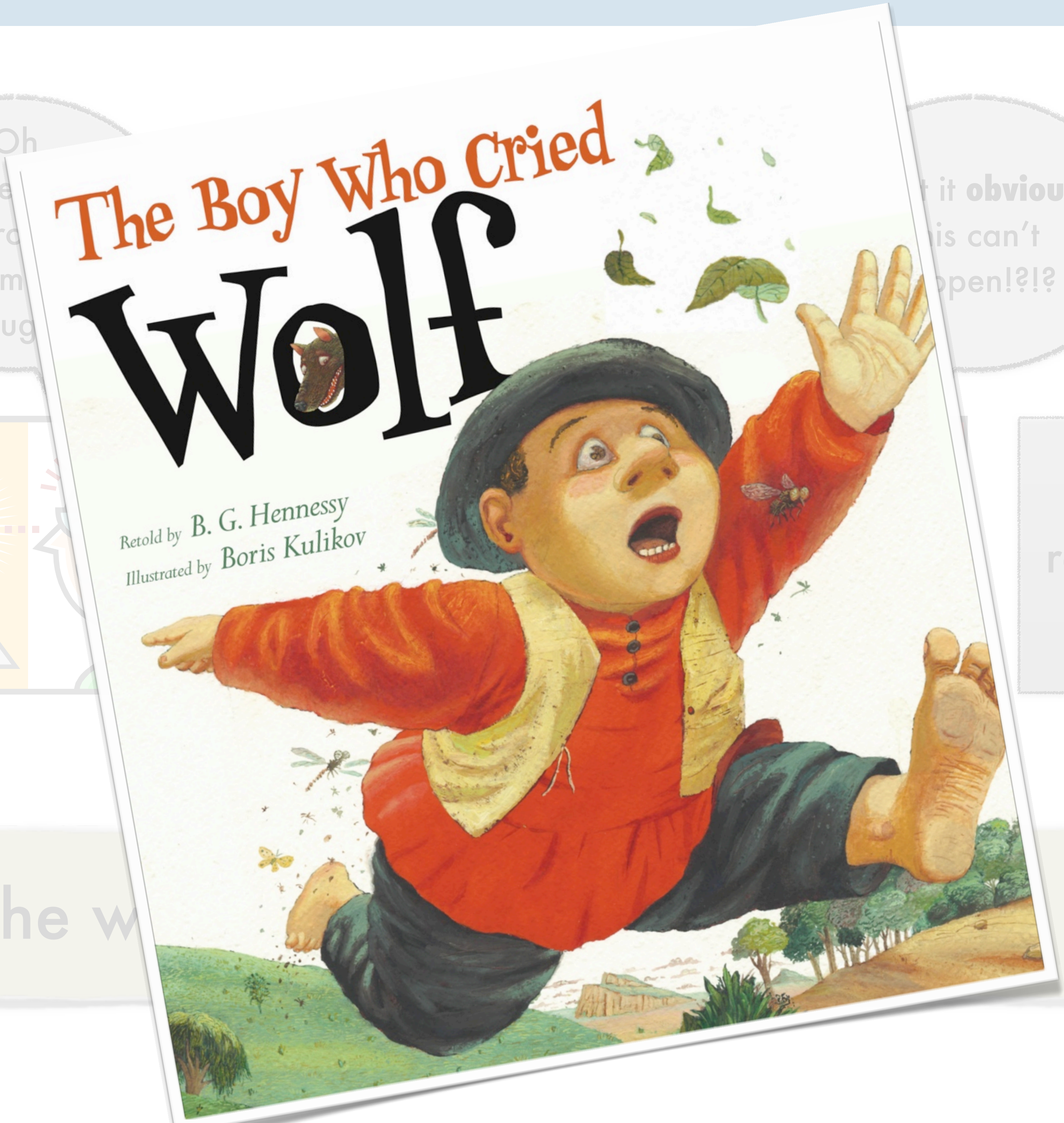


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"[M]ore than a 30% [false alarm rate] easily causes problems. True bugs get lost in the false. A vicious cycle starts where low trust causes complex [true] bugs to be labeled false [alarms], leading to yet lower trust."

"A stupid false [alarm] implies the tool is stupid."

Bessey, A., Block, K., Chelf, B., Chou, A., Fulton, B., Hallem, S., Henri-Gros, C., Kamsky, A., McPeak, S. and Engler, D. 2010. A few billion lines of code later: using static analysis to find bugs in the real world. *Commun. ACM*. 53, 2 (2010), 66–75.

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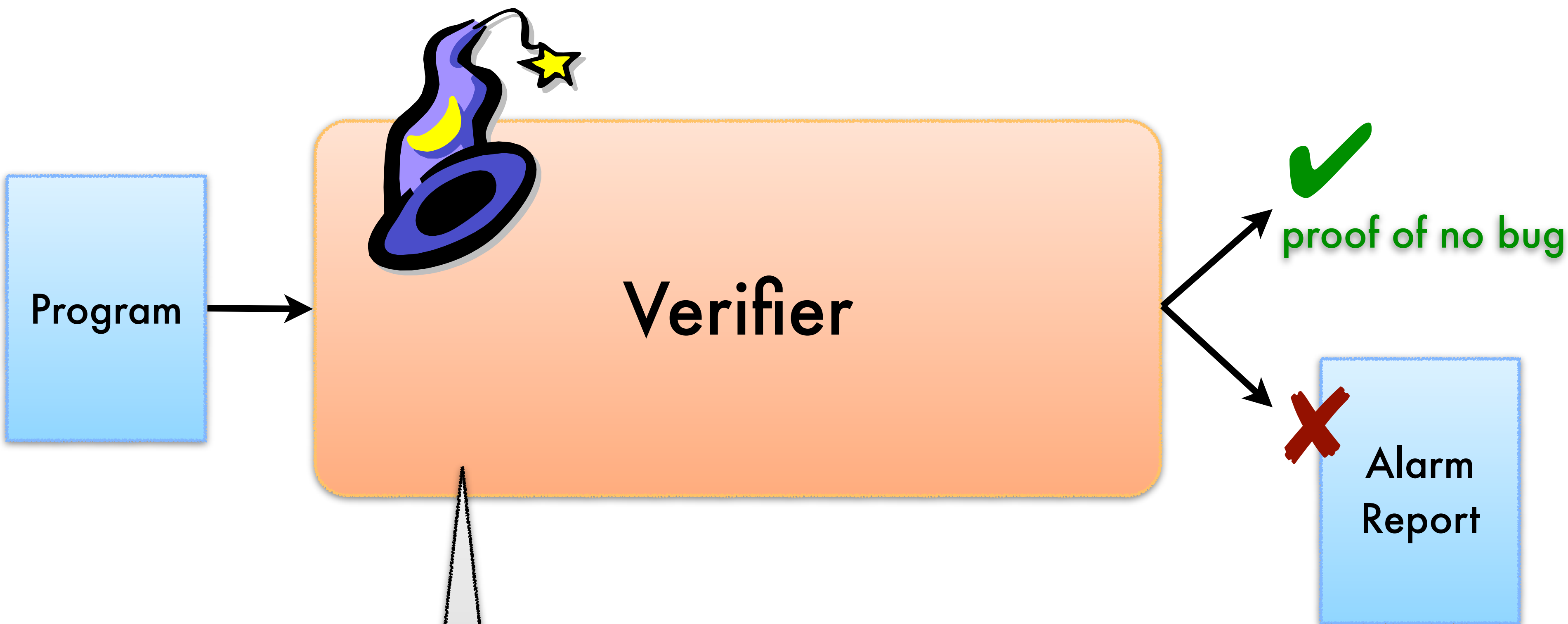


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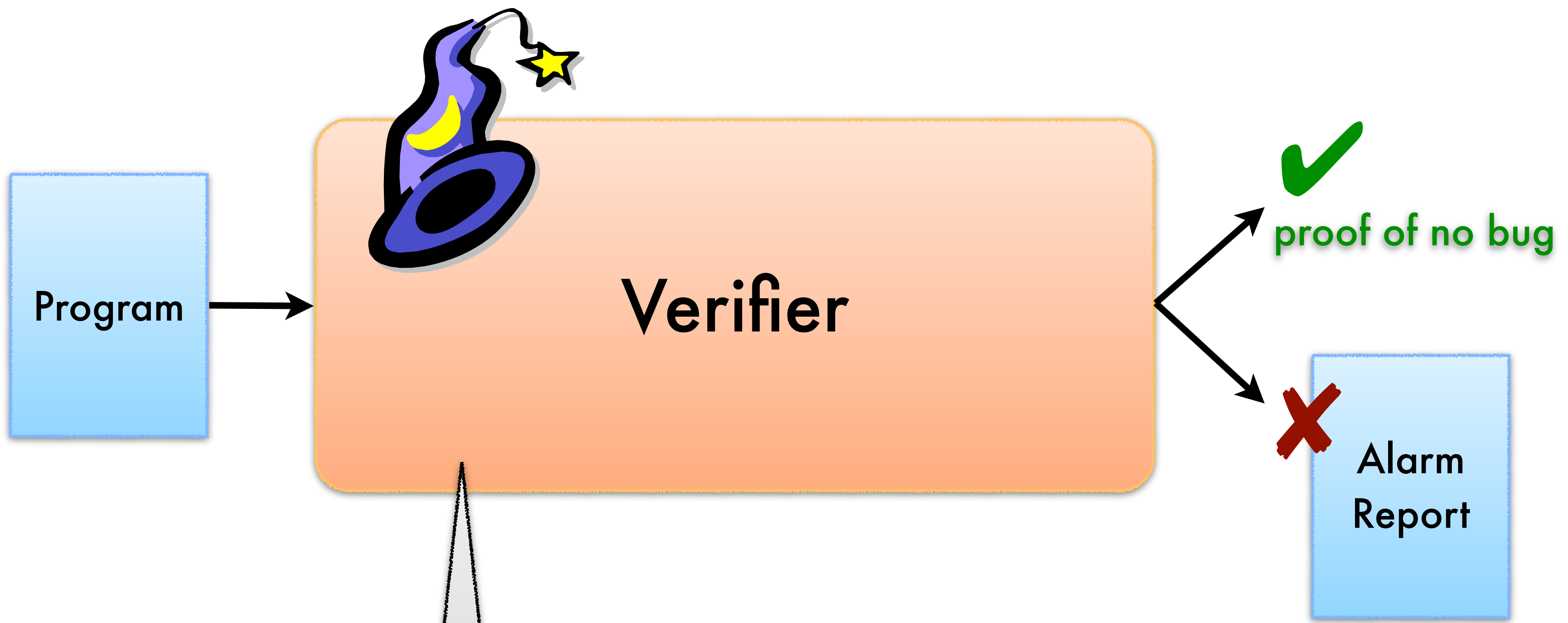


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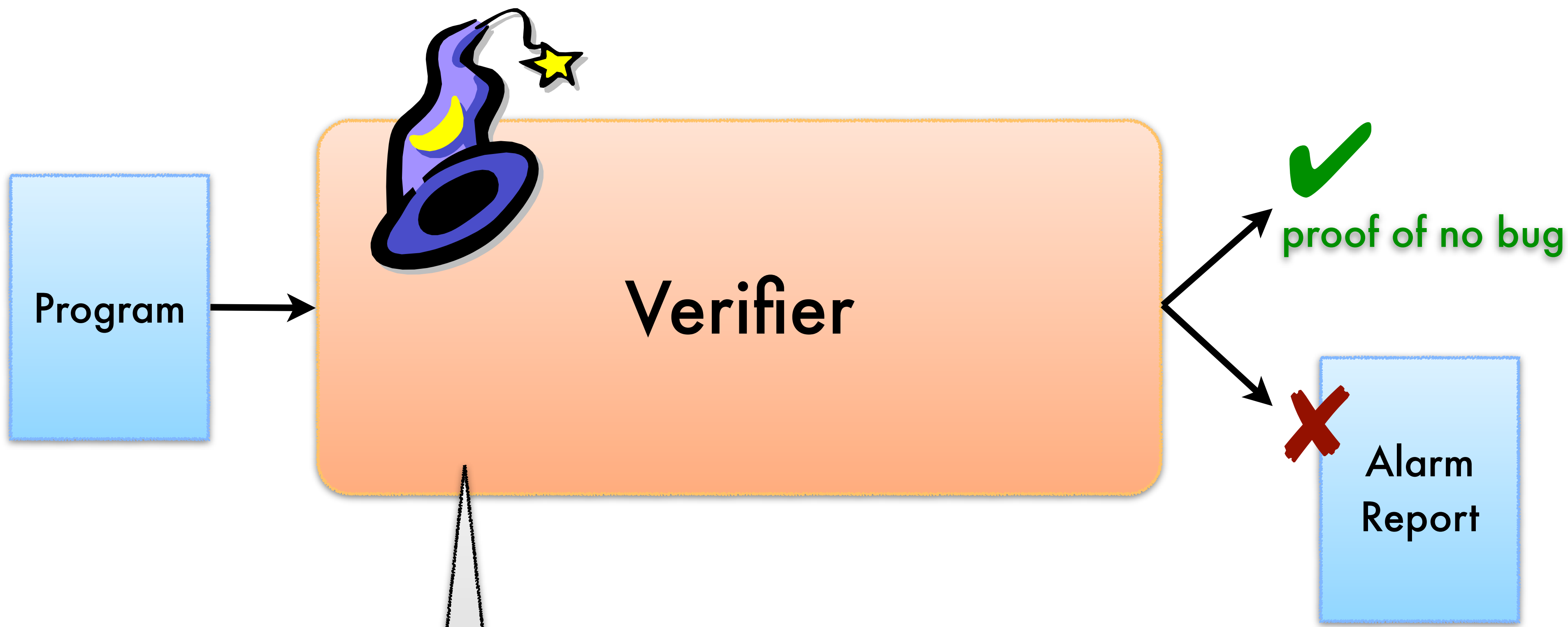


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But it can never be perfect (undecidability)

Also not a sufficient "excuse"

## Agenda: The cooperative approach addresses the whole bug mitigation process.

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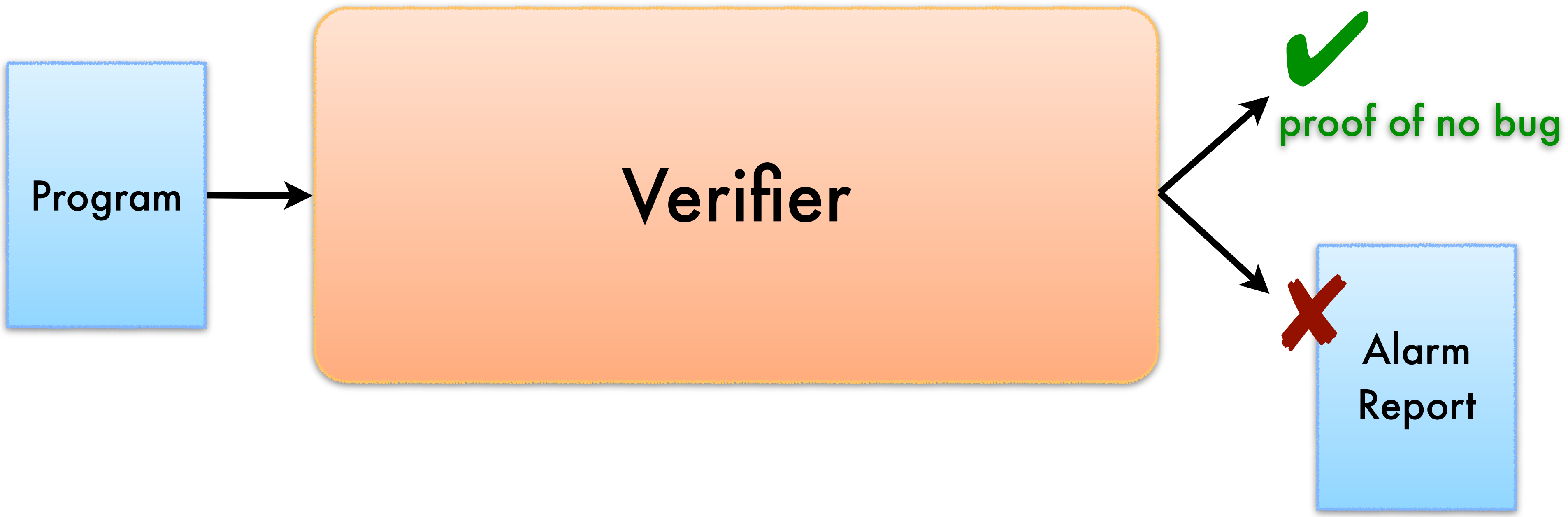

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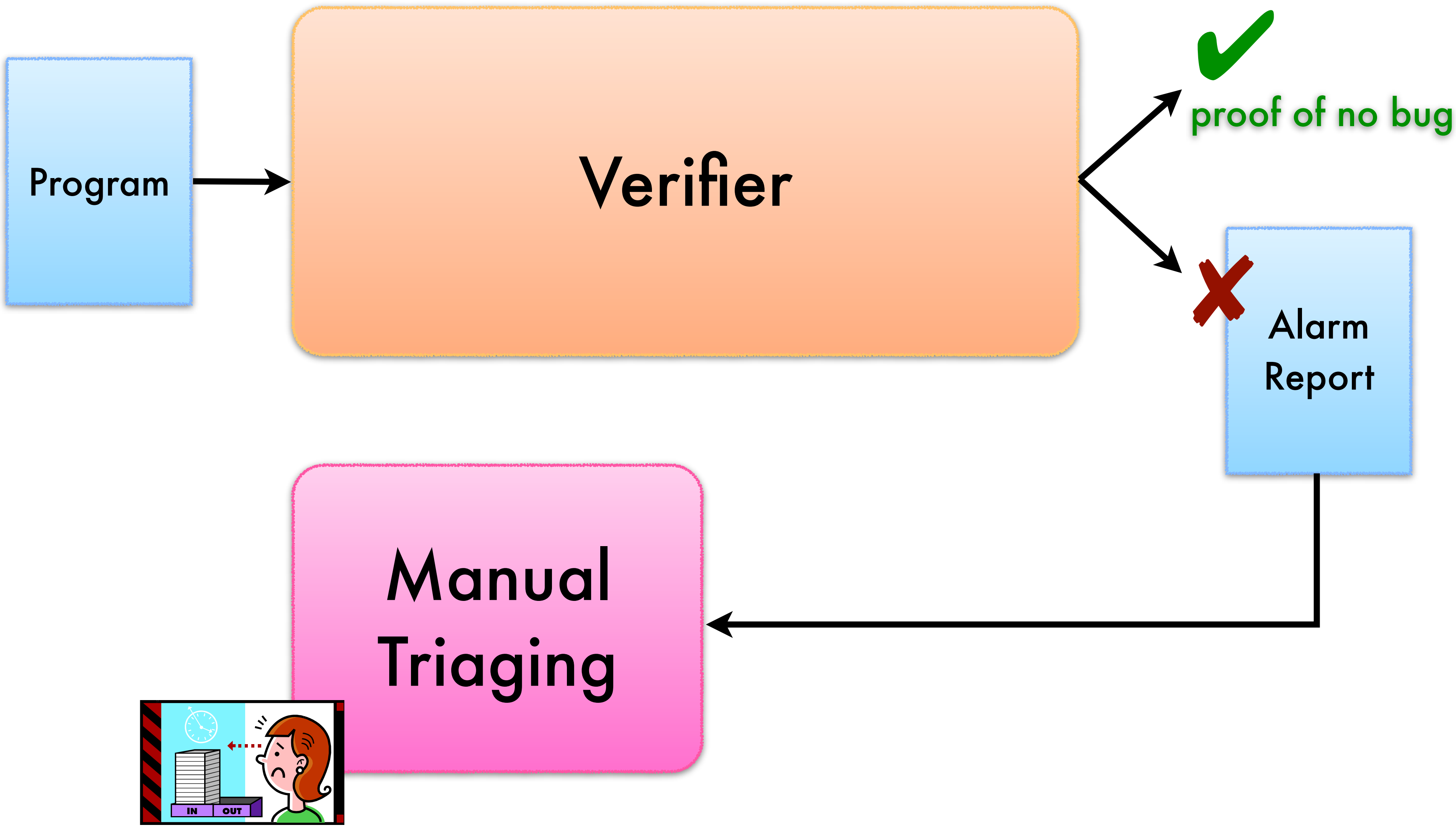

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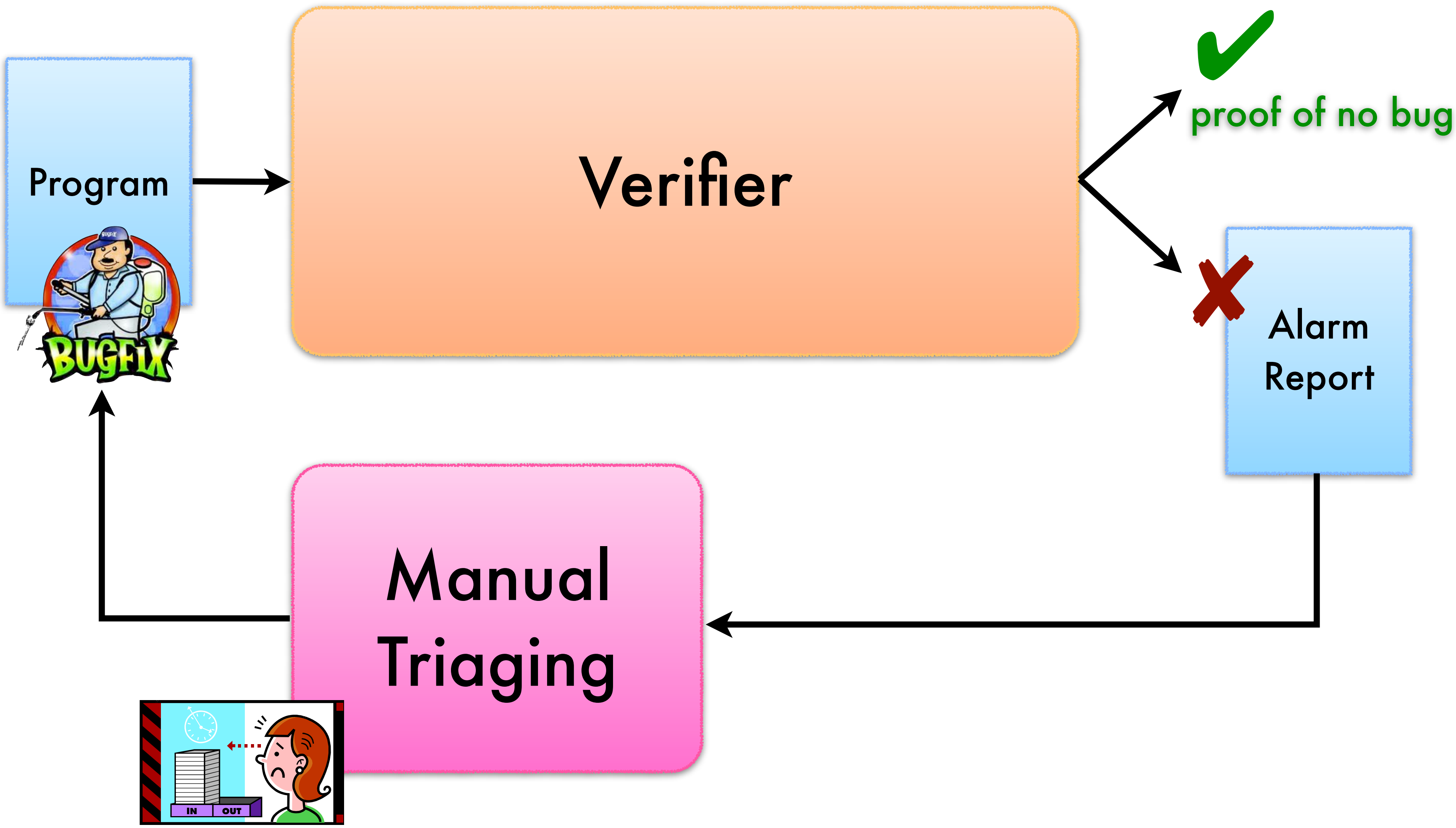

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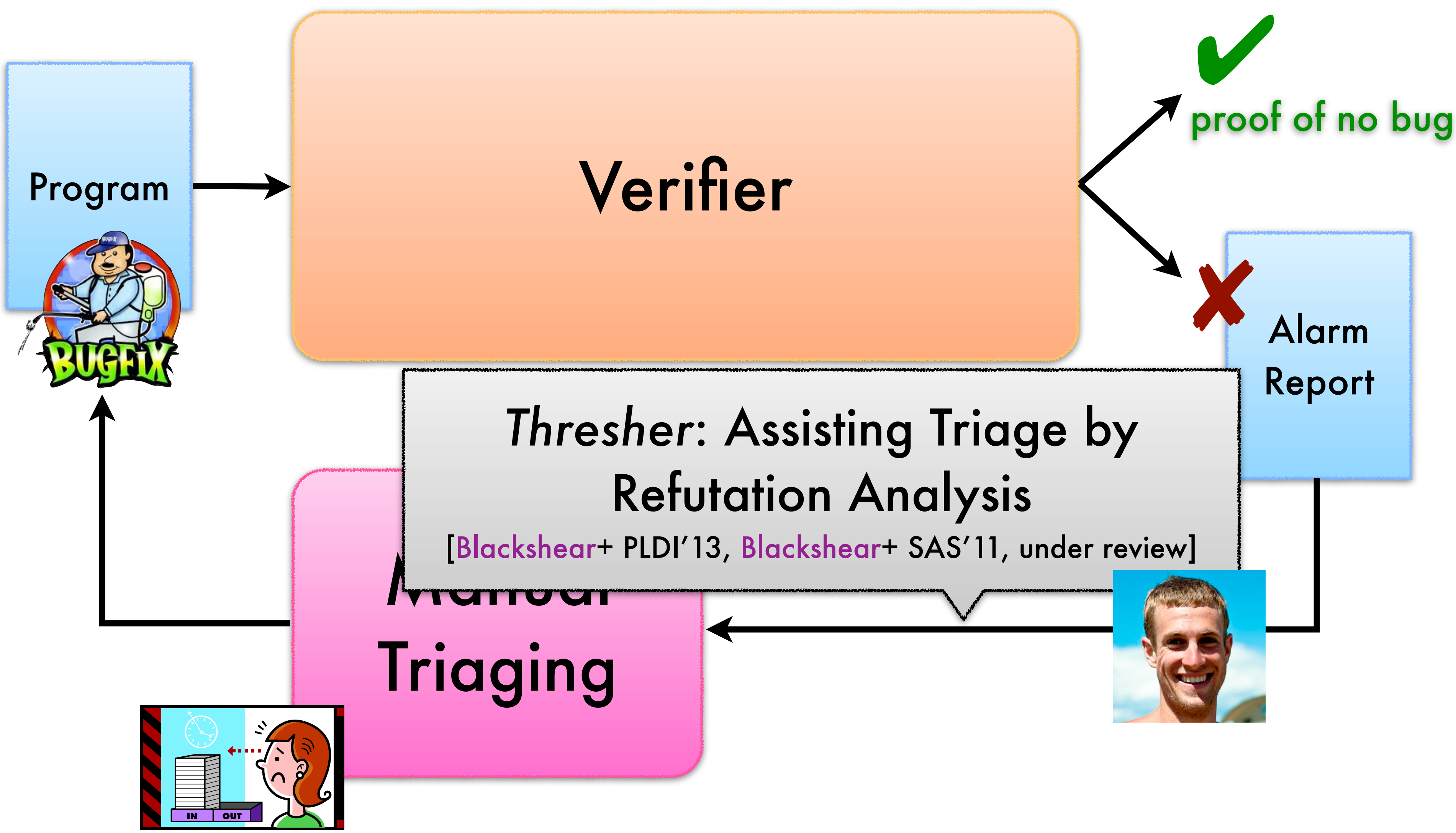

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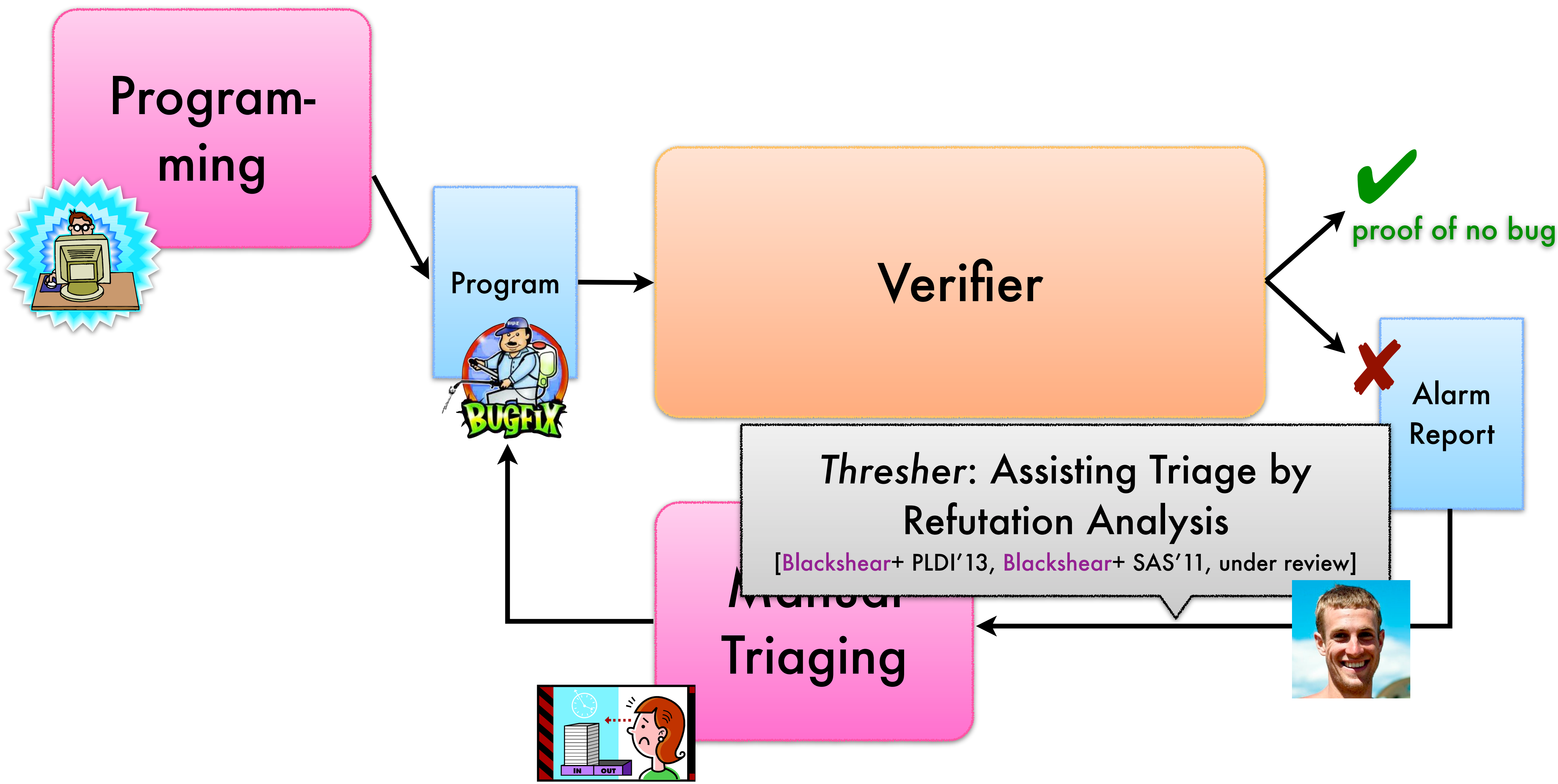

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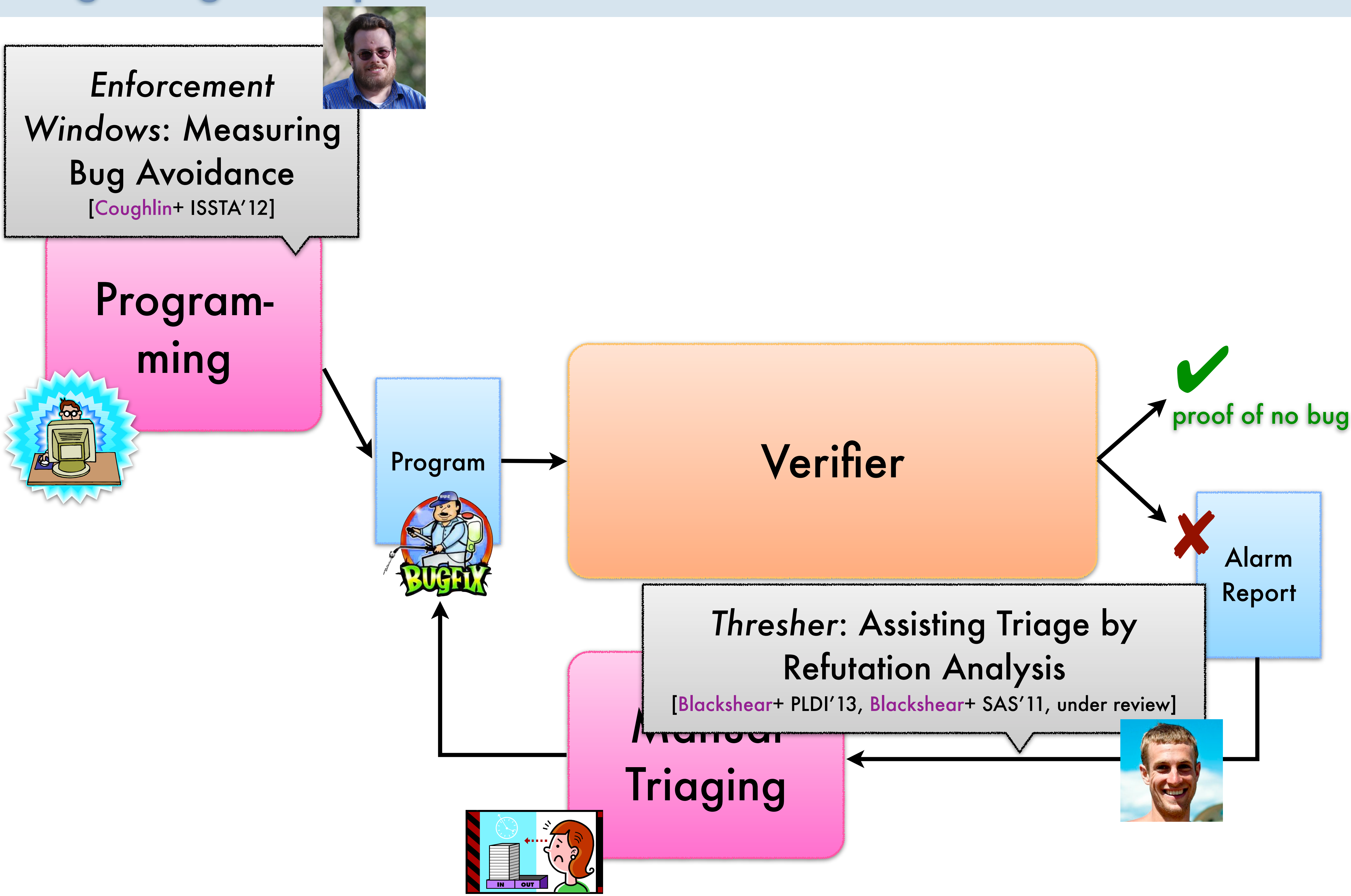

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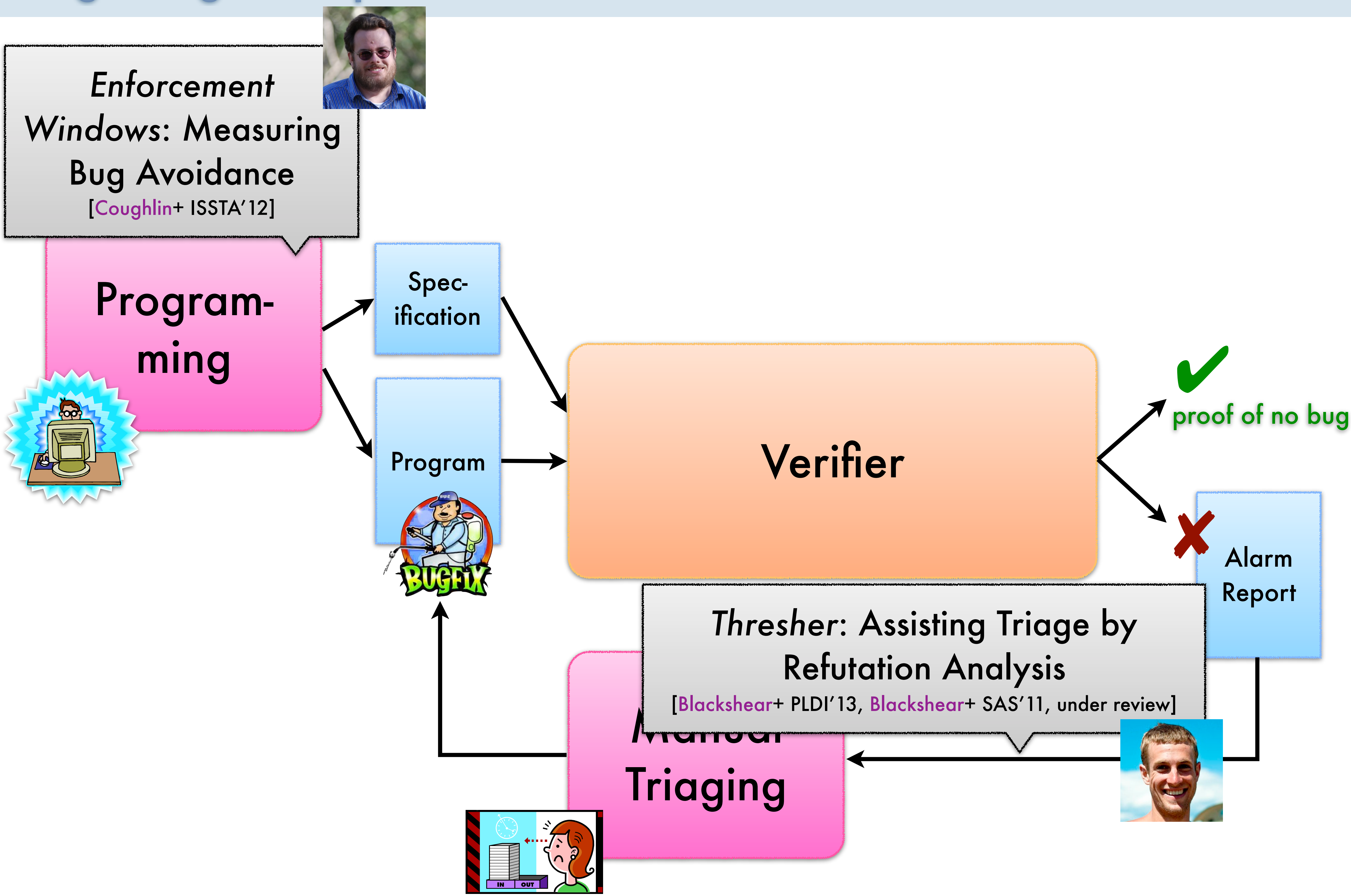

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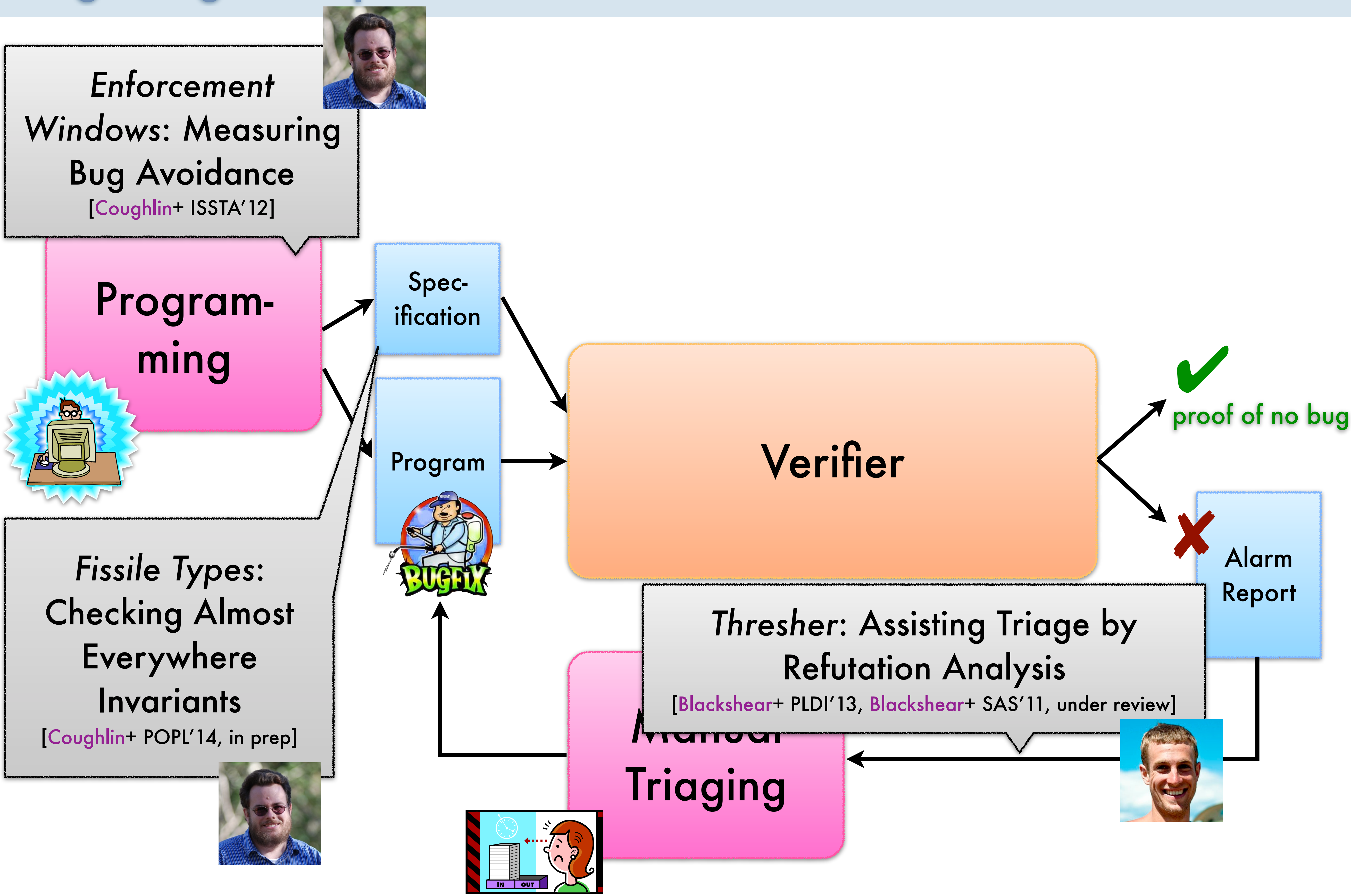

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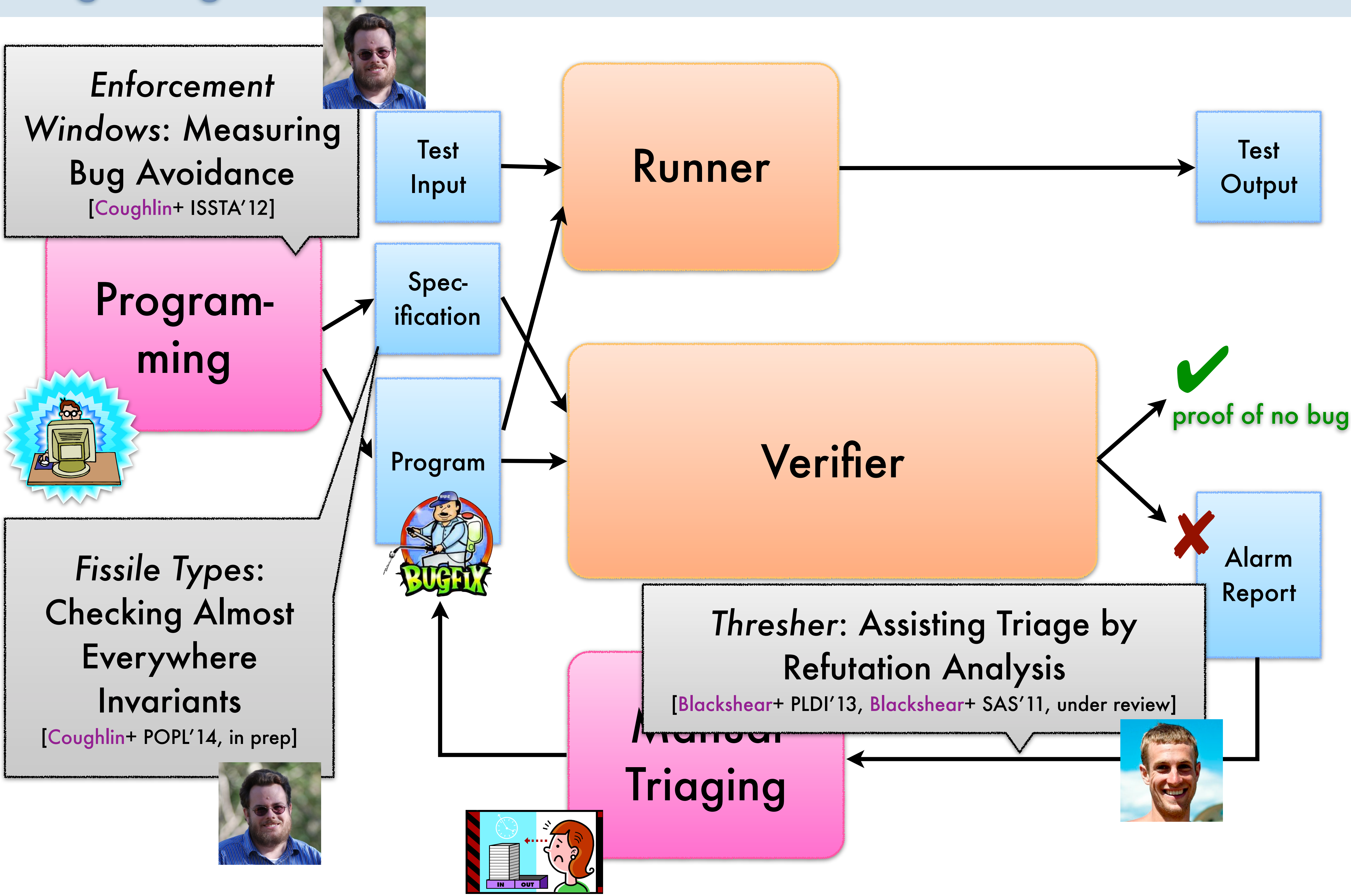

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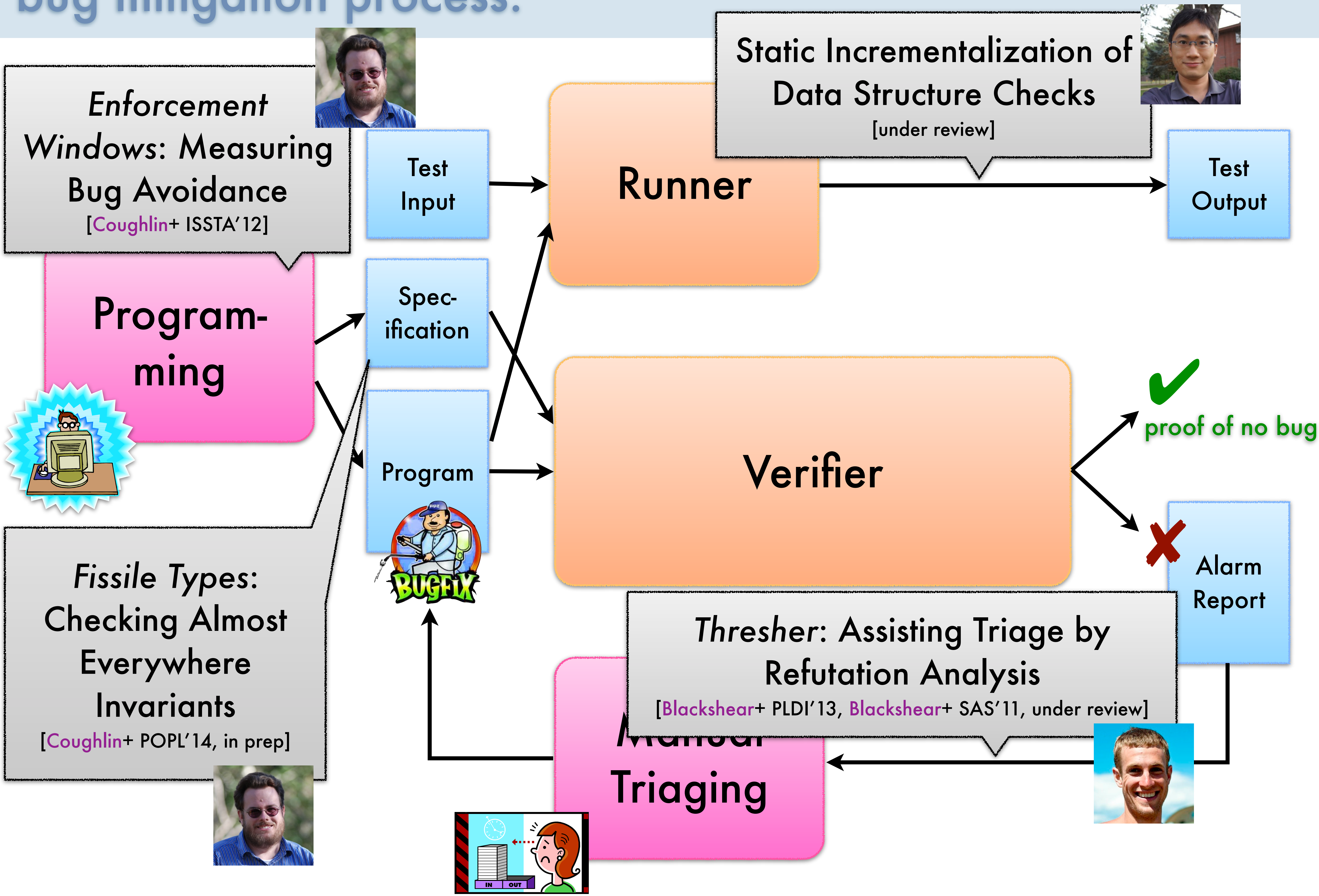

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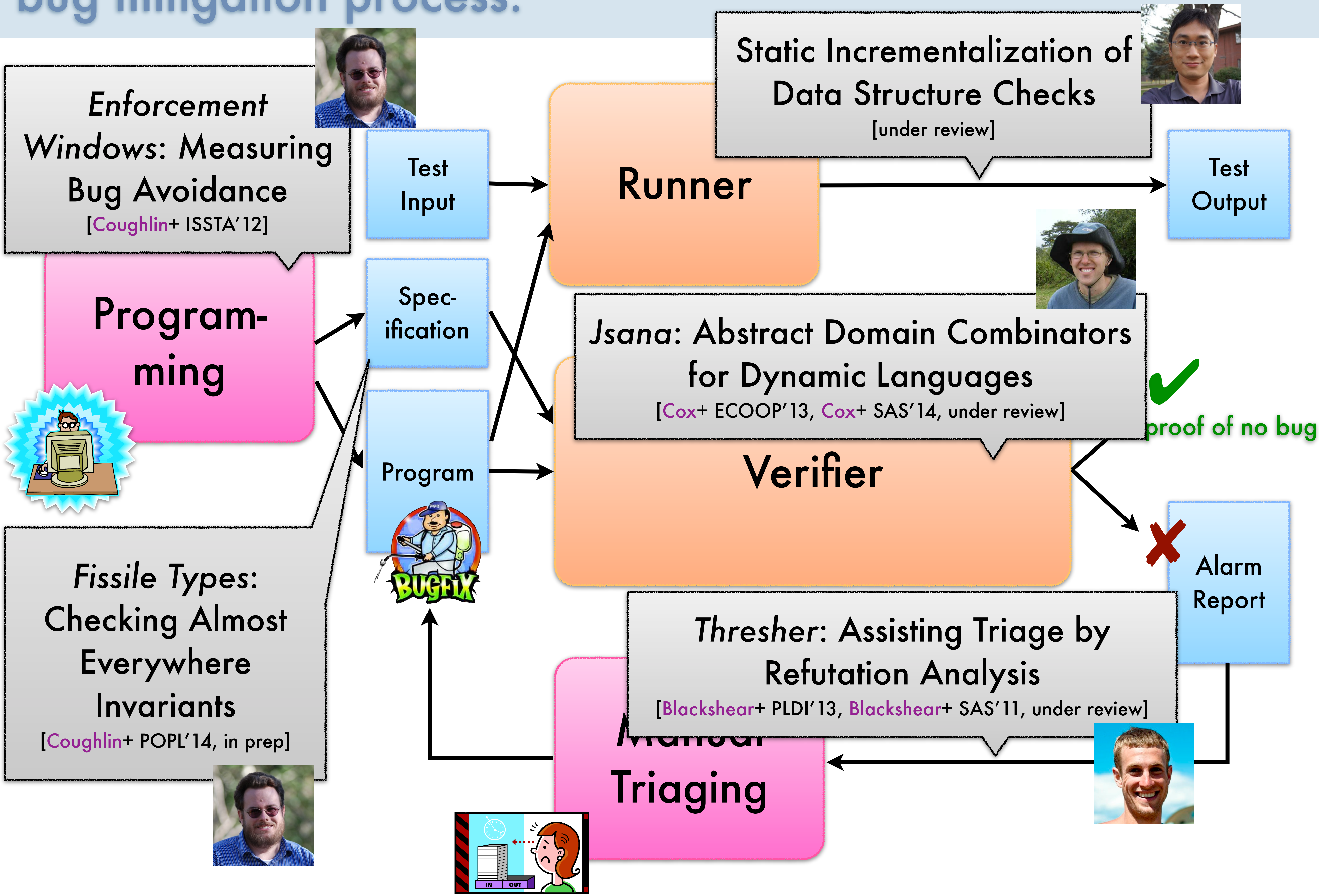

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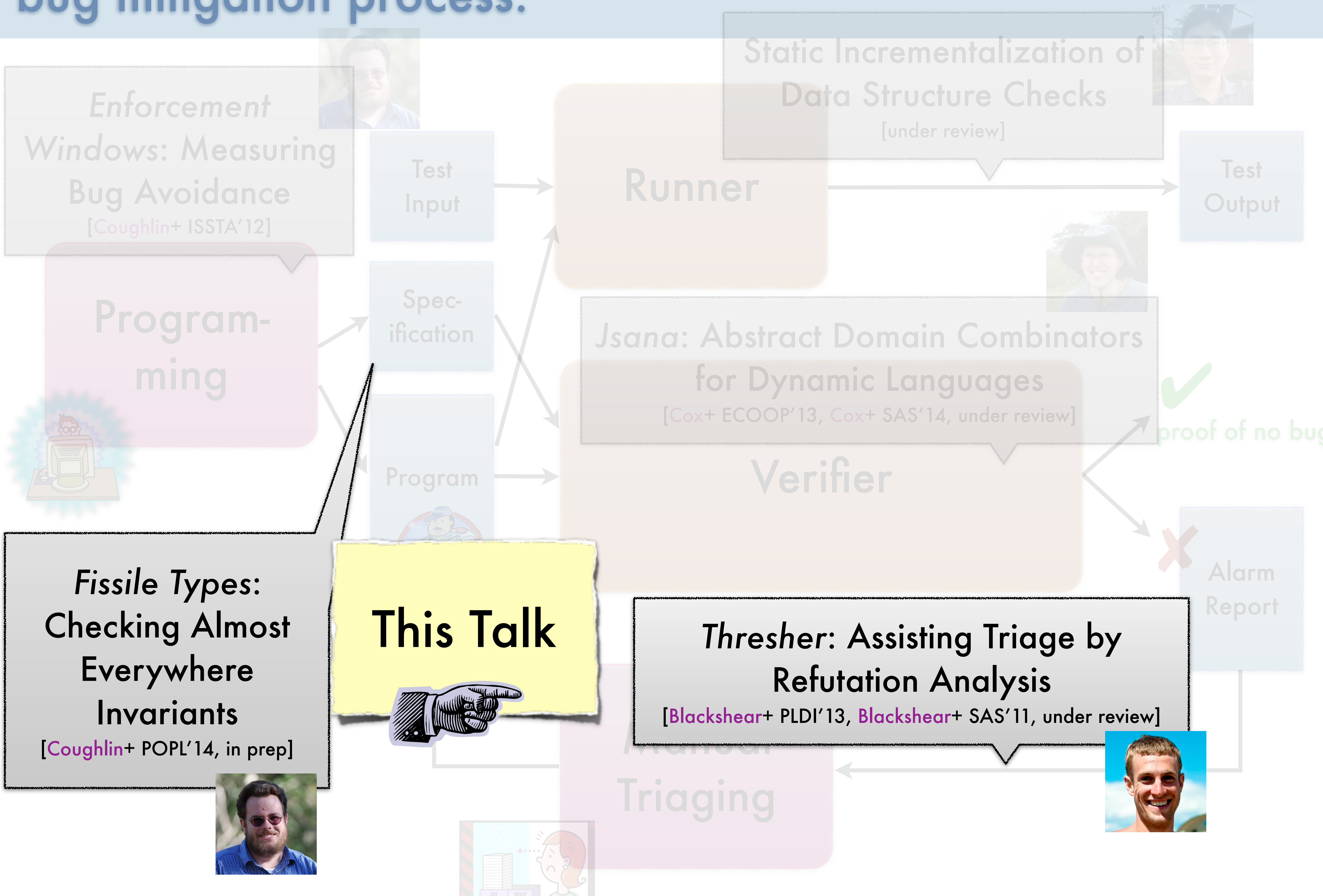

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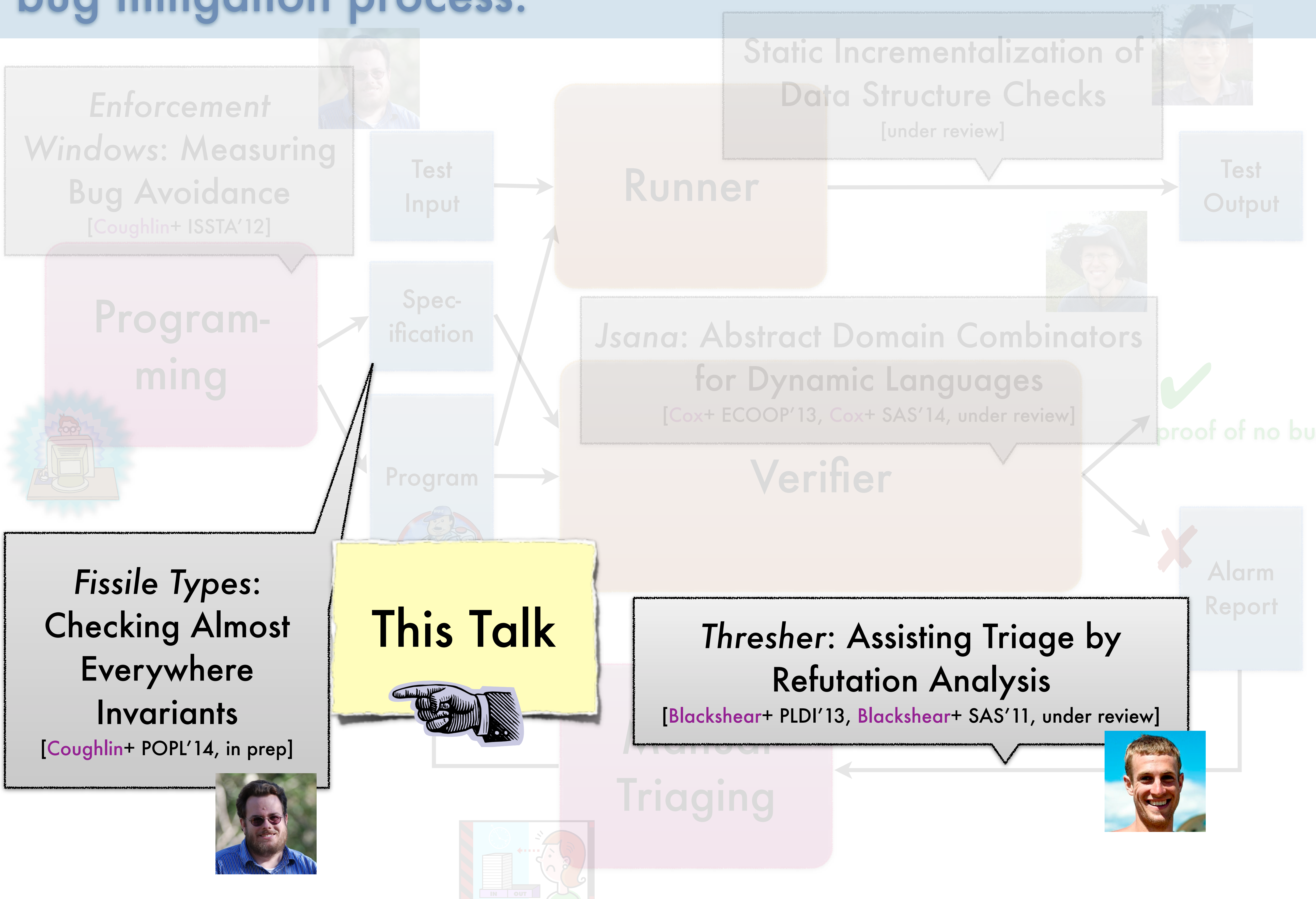

# This Talk: Highlights

Thresher: Precise Refutations for Heap Reachability

Assist in triage of queries about heap relations

- Idea: Assume alarms false, prove them so automatically
- Filters out ~90% of false alarms to expose true bugs
- Going from ~450 hours of manual work to ~30 hours
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Fissile Types: Checking Reflection with Almost Everywhere Invariants

Strengthen type checking with symbolic analysis

- Interactive checking speeds: making IDE integration possible
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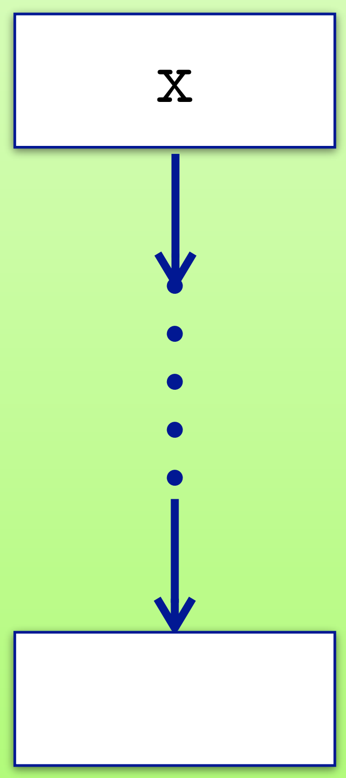


of type T ?

Example

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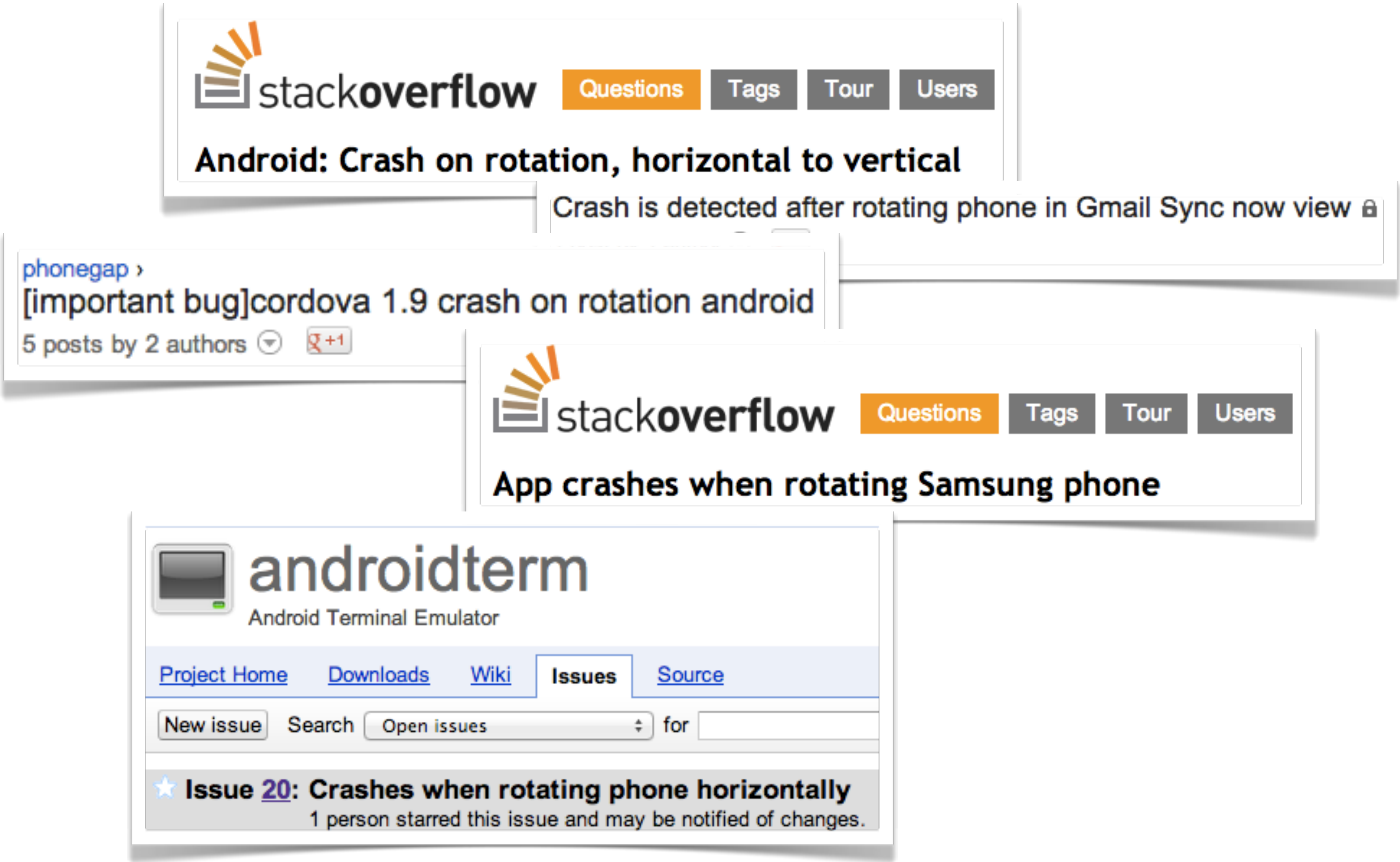

# How is this useful? We identify memory leaks that cause your app to crash!

# Android memory leaks underly rotation-based crashes.

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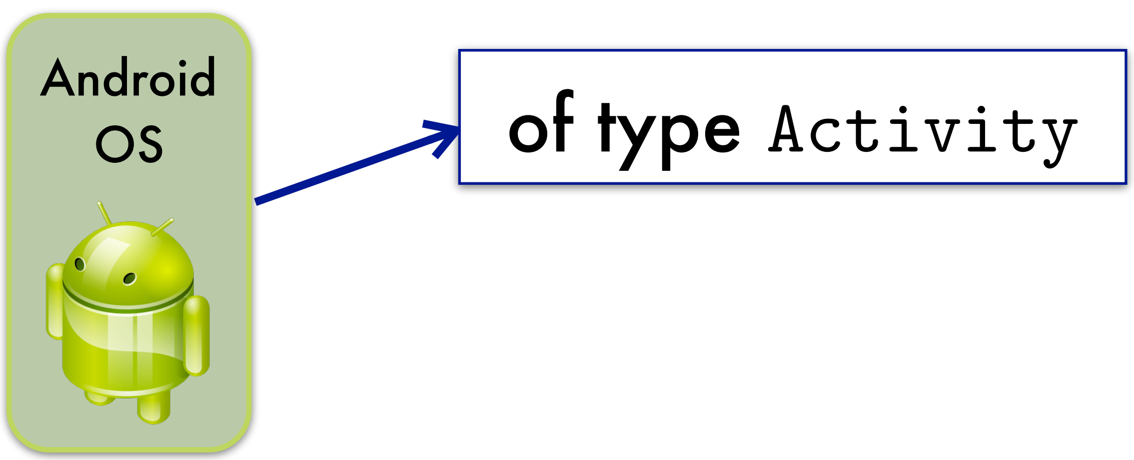


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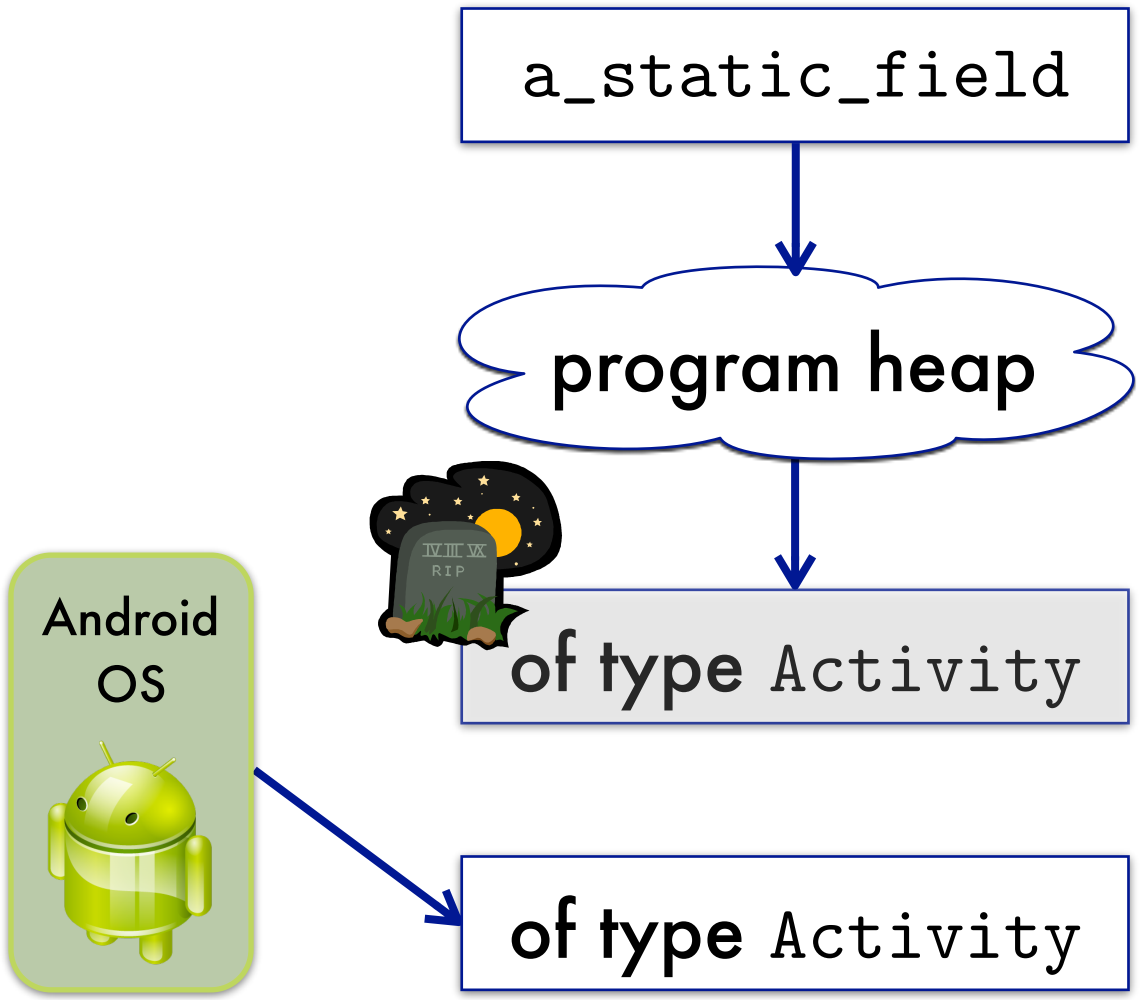


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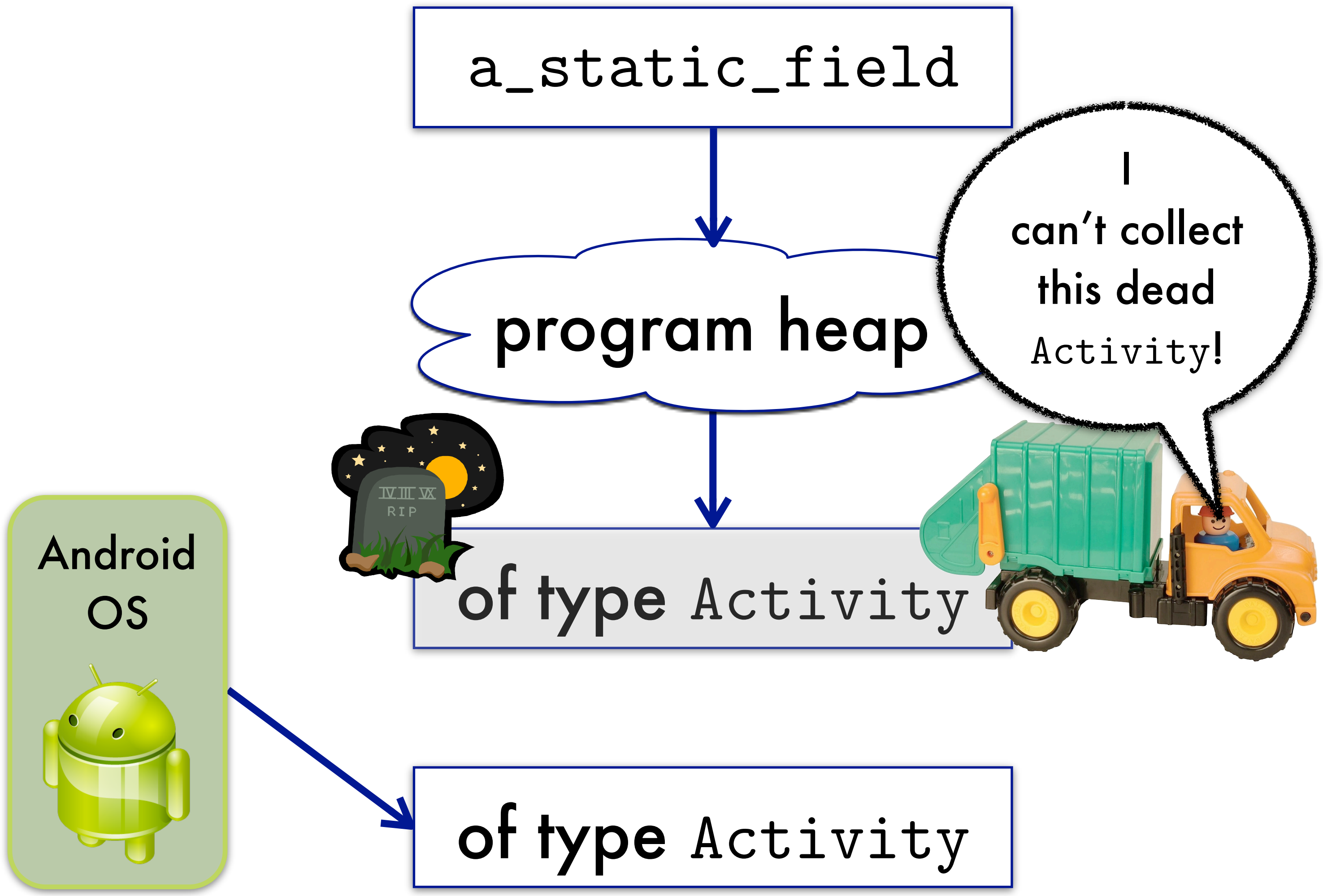


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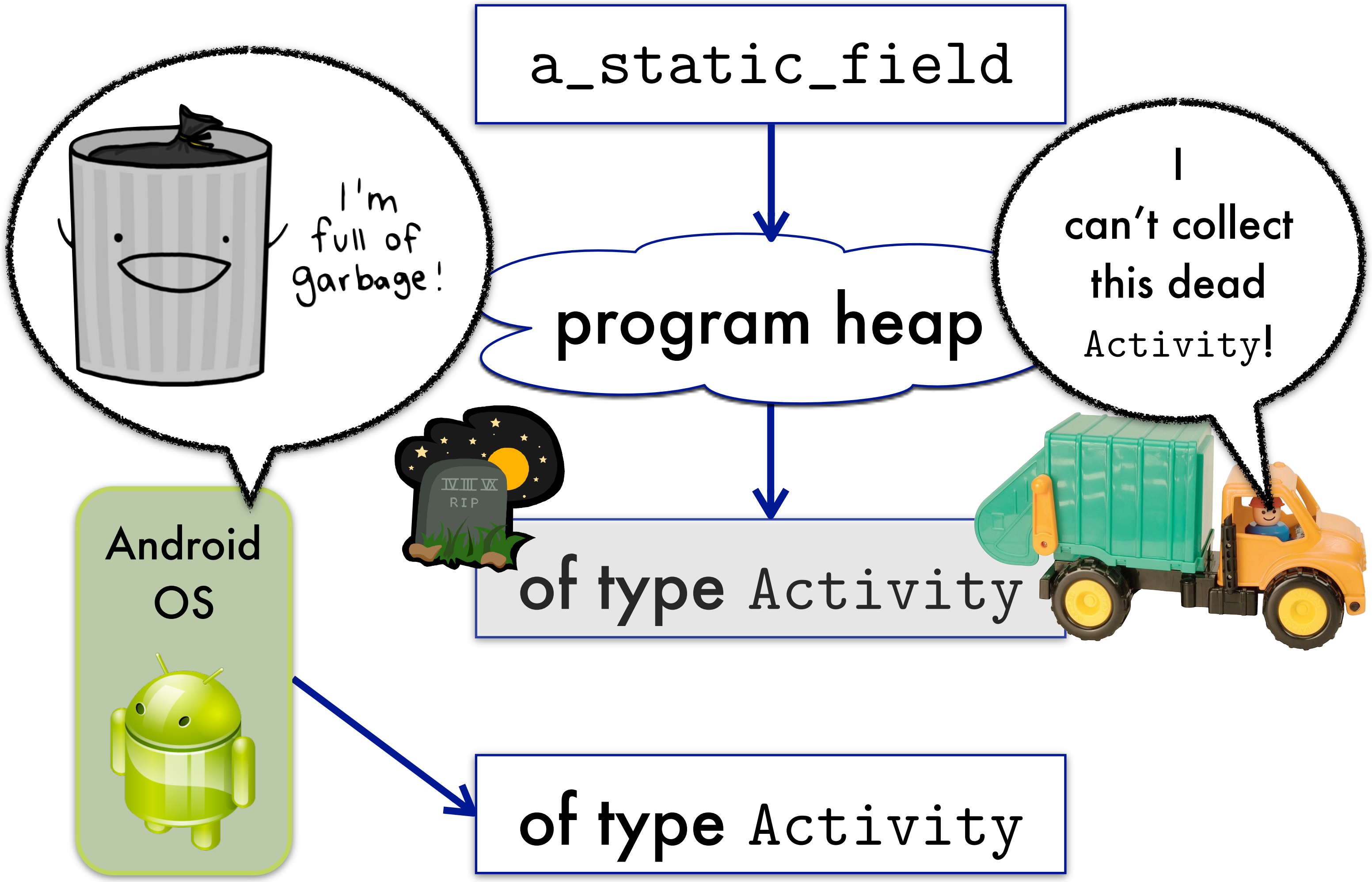


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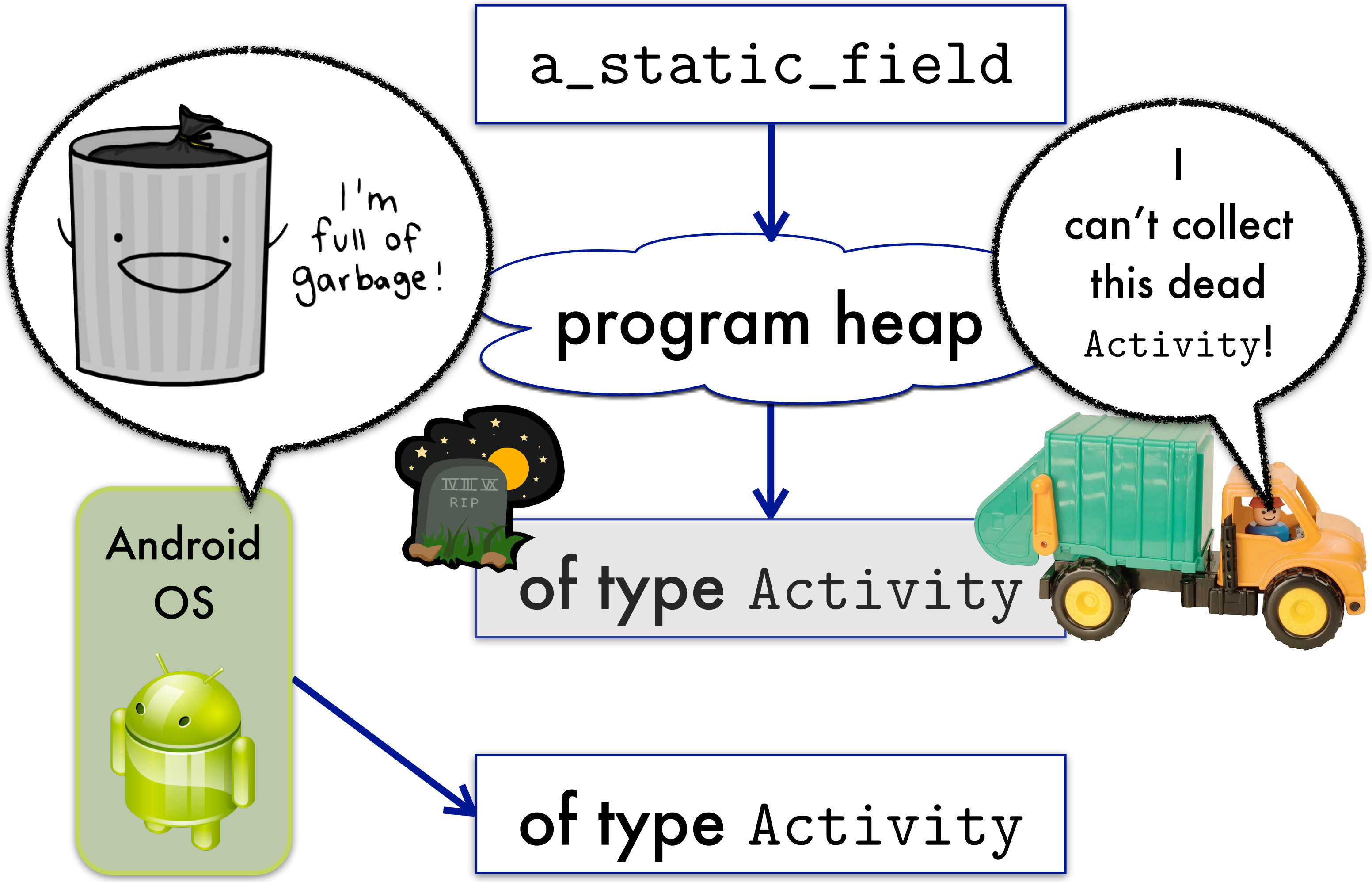


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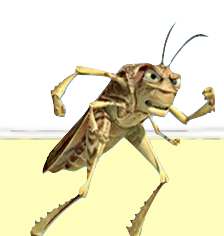

Bug: Holding reference to “old” Activity

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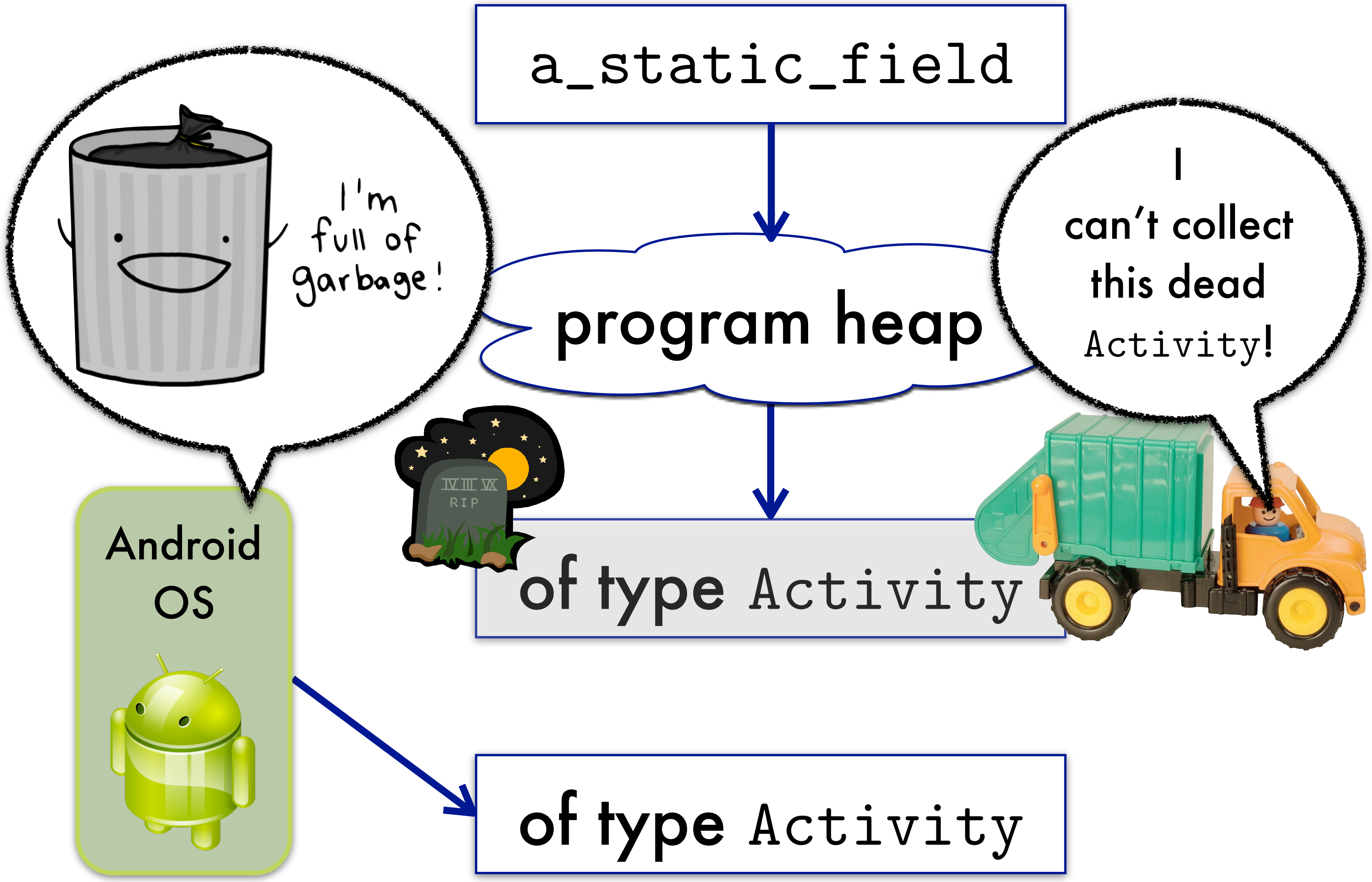
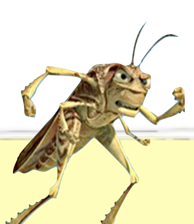



Activity objects encapsulate the UI

"an Activity leak"



Bug: Holding reference to "old" Activity

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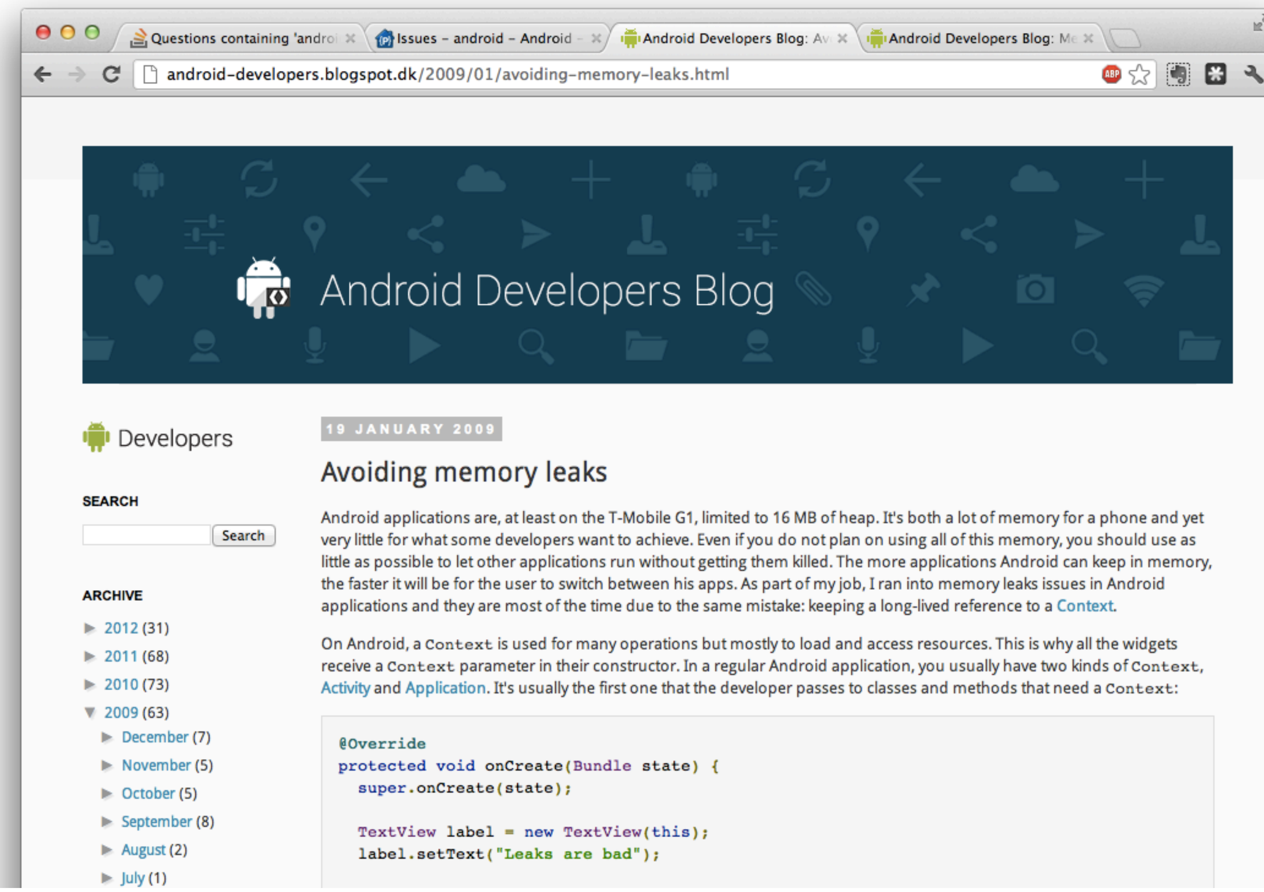
"Do not keep long-lived references to a context-activity"



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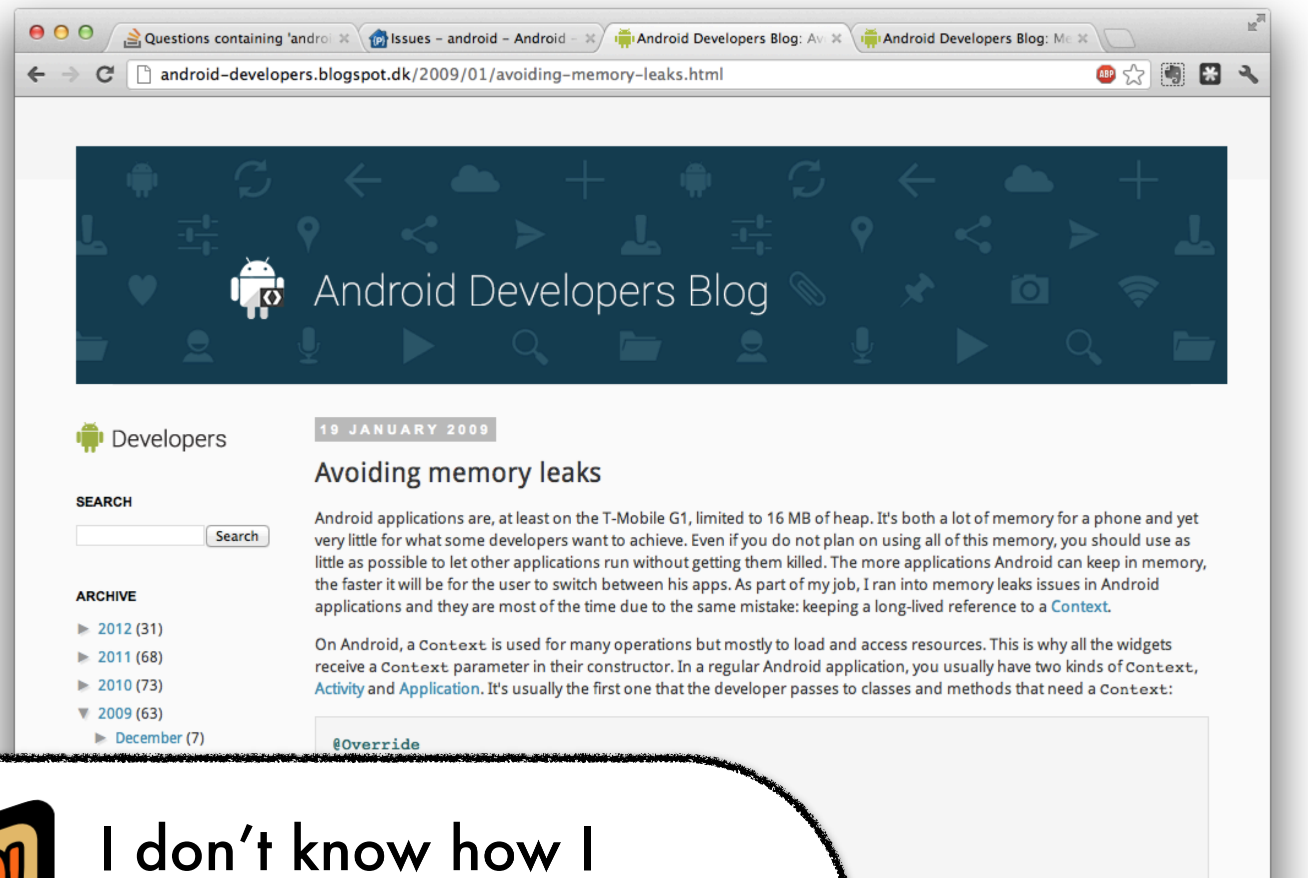


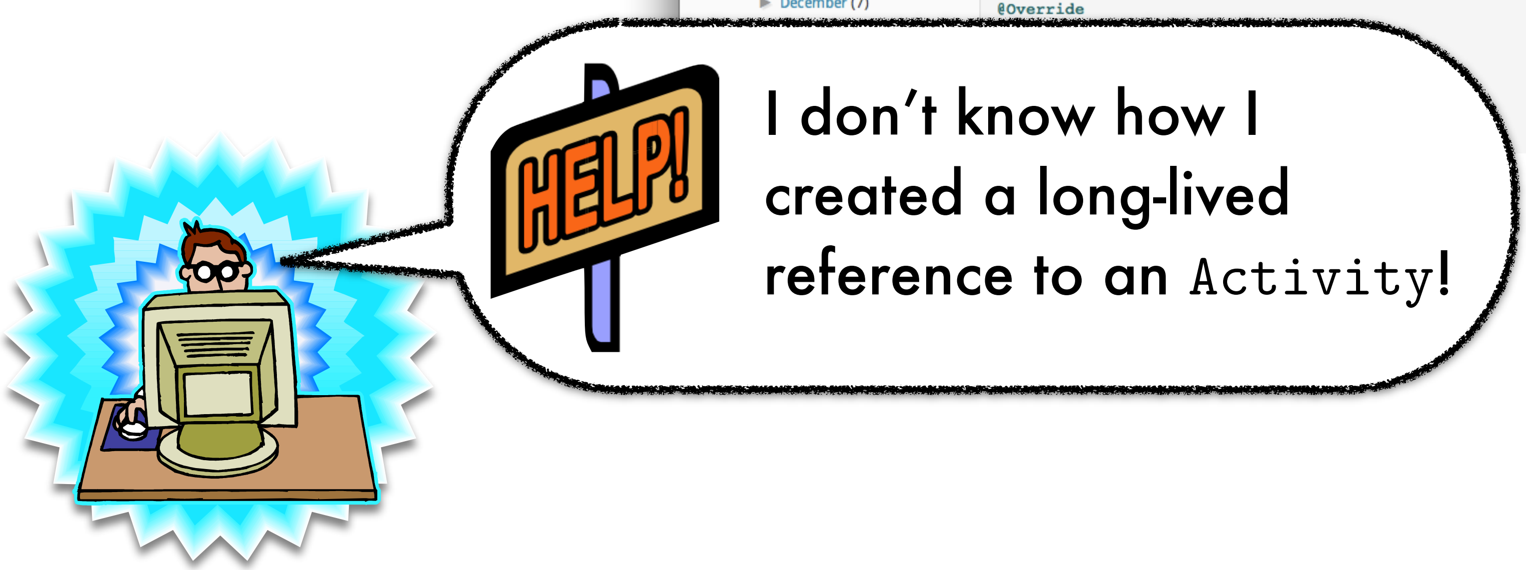

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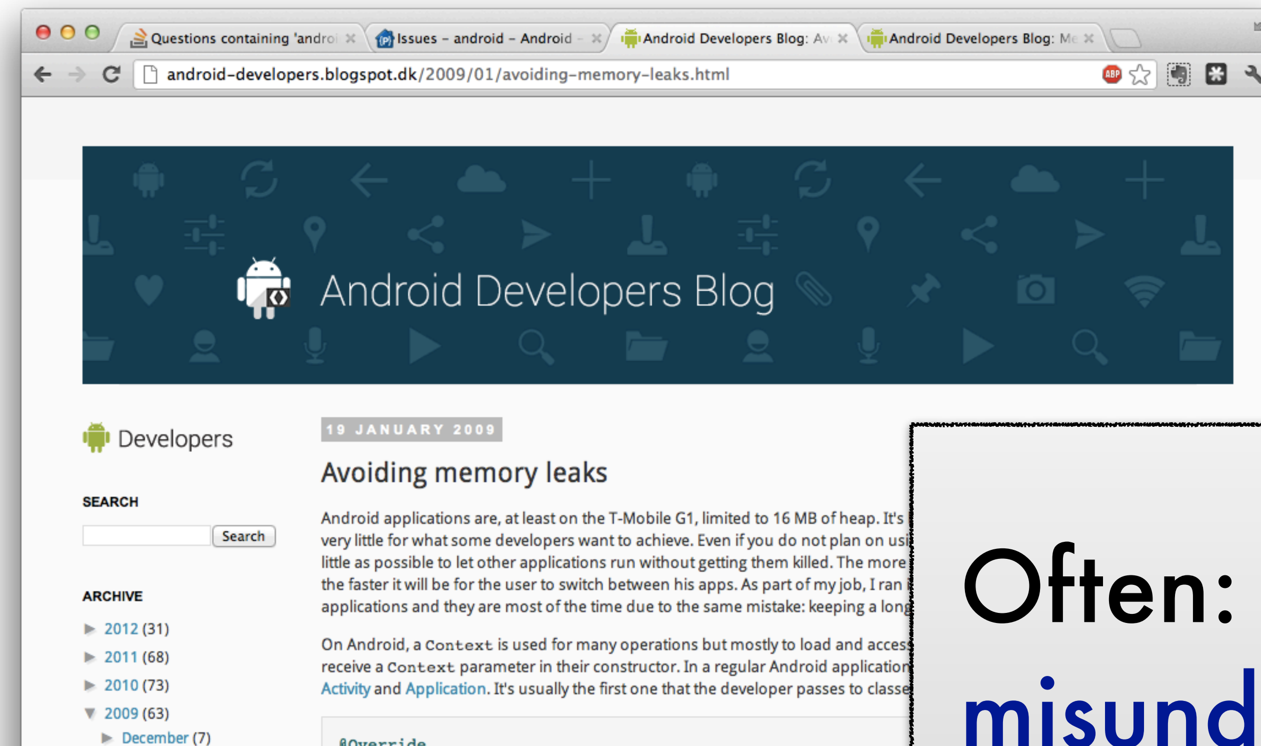
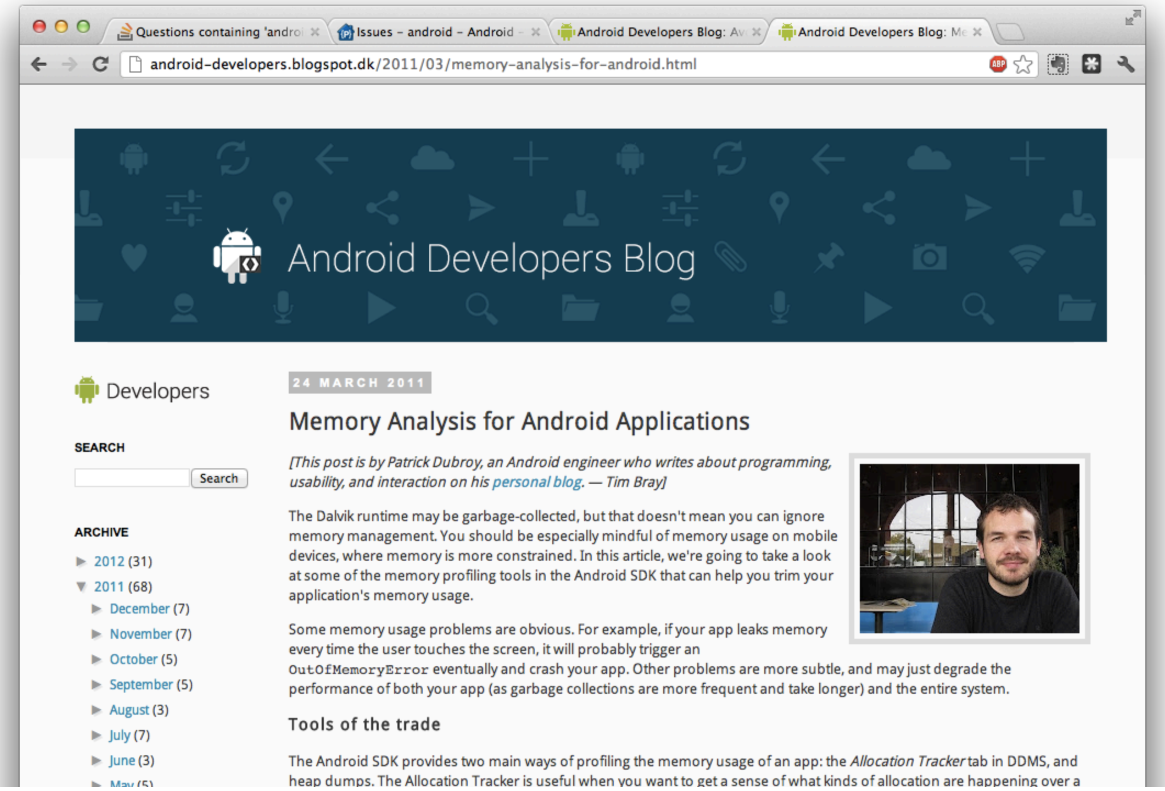




I don't know how I created a long-lived reference to an `Activity`!

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

# The state of practice in debugging `Activity` leaks ...



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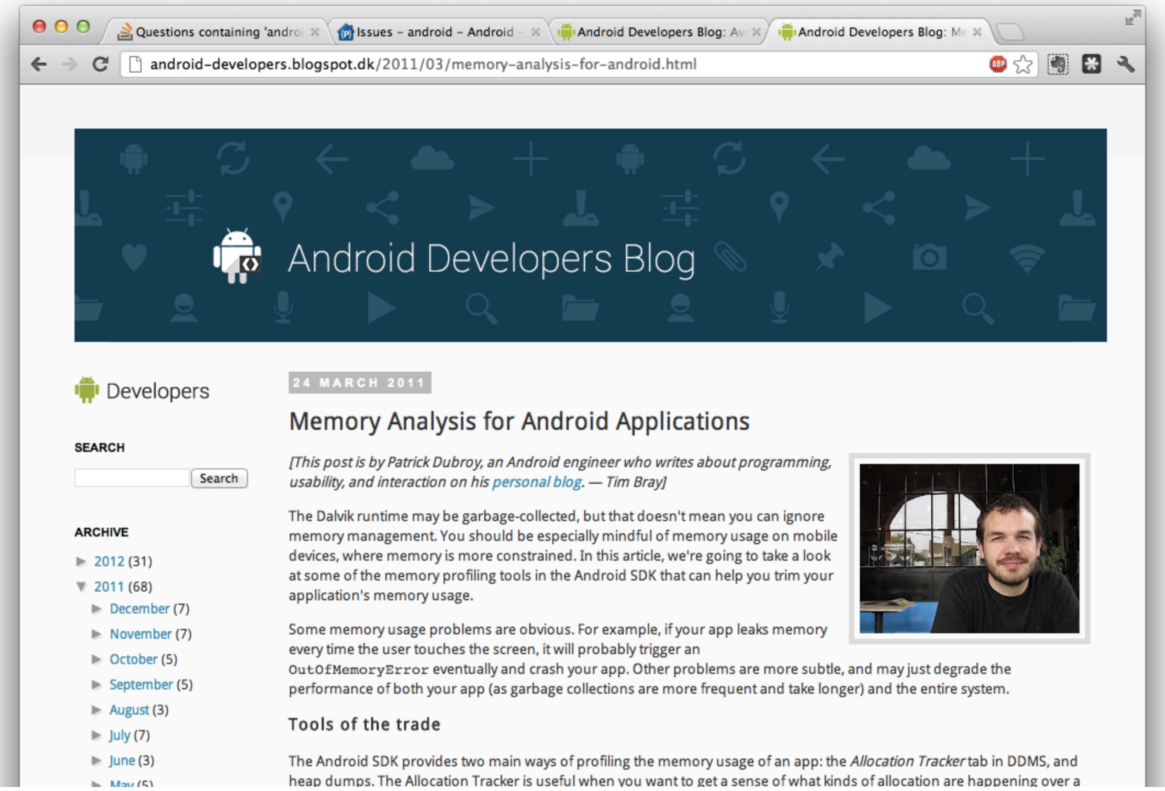


1. Run the app

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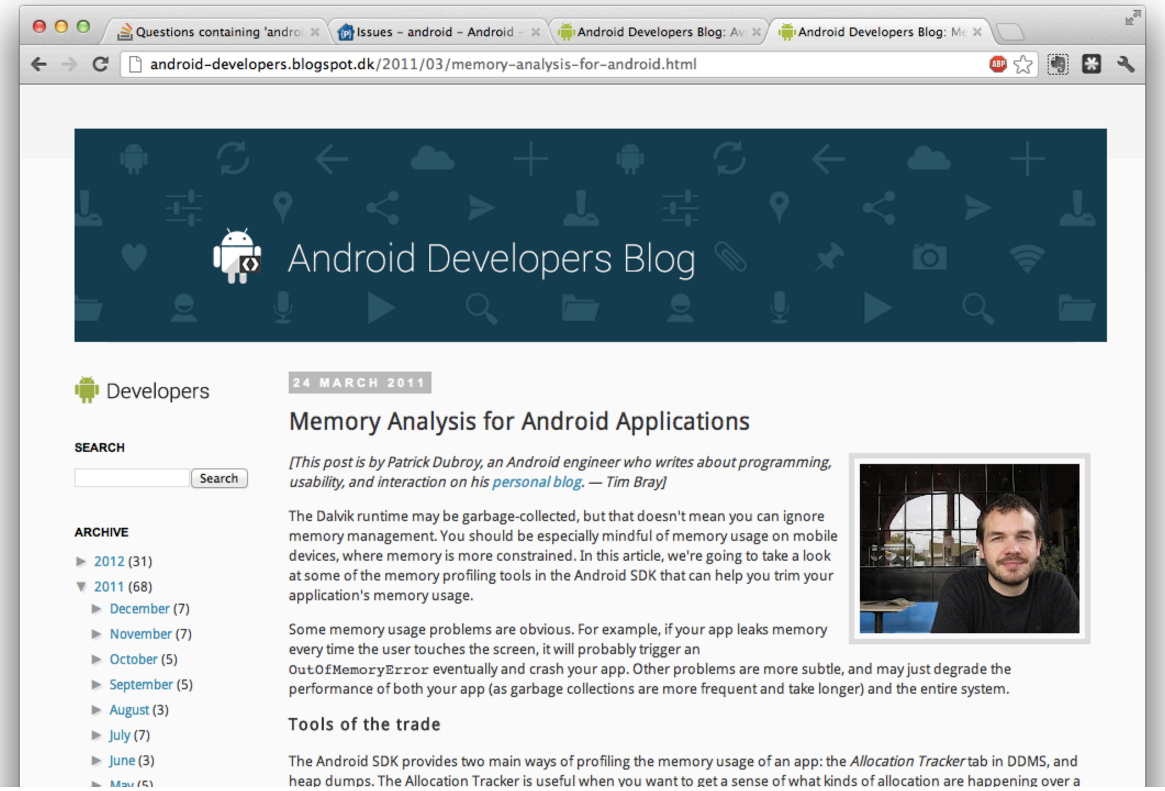


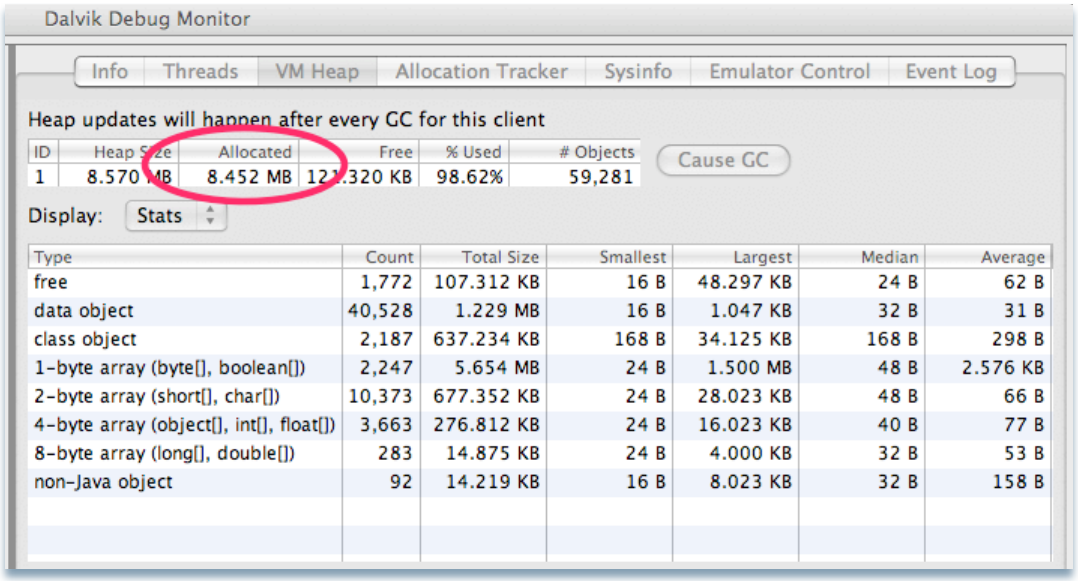


| ID | Heap Size | Allocated | Free | % Used | # Objects |
|---|---|---|---|---|---|
| 1 | 8.570 MB | 8.452 MB | 121.320 KB | 98.62% | 59,281 |

| Type | Count | Total Size | Smallest | Largest | Median | Average |
|---|---|---|---|---|---|---|
| free | 1,772 | 107.312 KB | 16 B | 48.297 KB | 24 B | 62 B |
| data object | 40,528 | 1.229 MB | 16 B | 1.047 KB | 32 B | 31 B |
| class object | 2,187 | 637.234 KB | 168 B | 34.125 KB | 168 B | 298 B |
| 1-byte array (byte[], boolean[]) | 2,247 | 5.654 MB | 24 B | 1.500 MB | 48 B | 2.576 KB |
| 2-byte array (short[], char[]) | 10,373 | 677.352 KB | 24 B | 28.023 KB | 48 B | 66 B |
| 4-byte array (object[], int[], float[]) | 3,663 | 276.812 KB | 24 B | 16.023 KB | 40 B | 77 B |
| 8-byte array (long[], double[]) | 283 | 14.875 KB | 24 B | 4.000 KB | 32 B | 53 B |
| non-Java object | 92 | 14.219 KB | 16 B | 8.023 KB | 32 B | 158 B |

1. Run the app
2. Watch the heap usage

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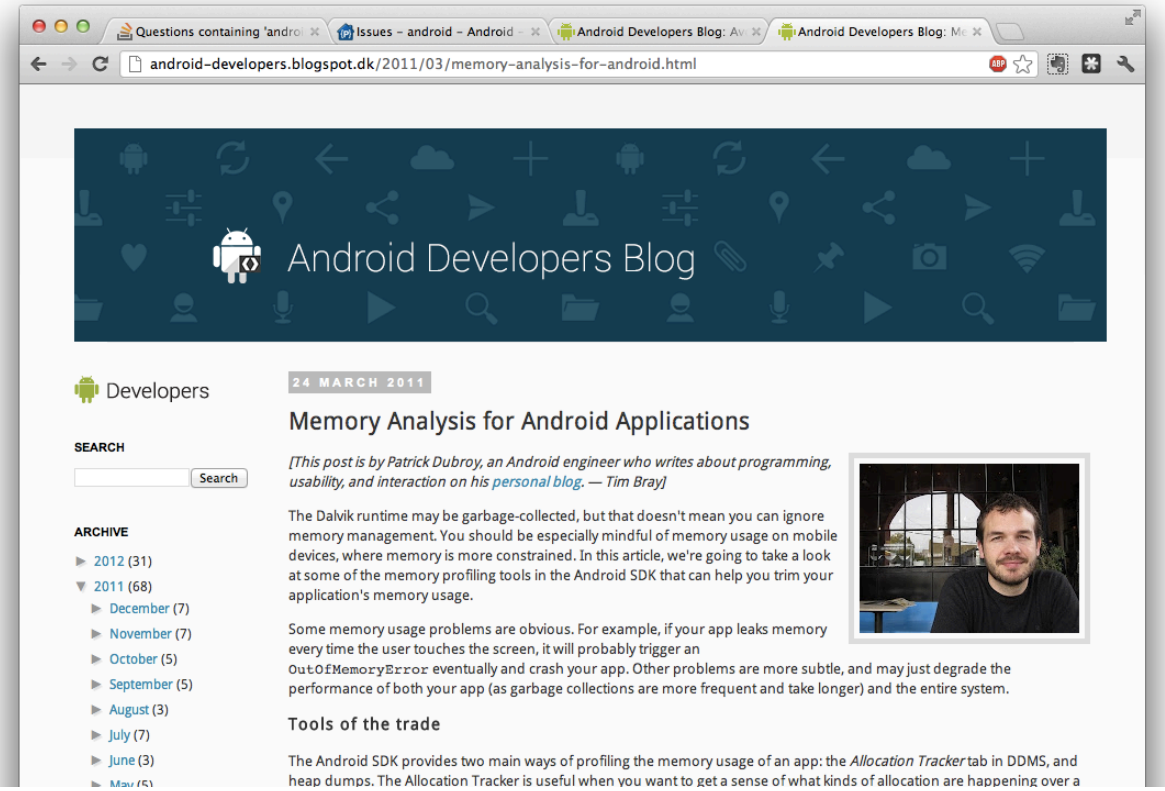
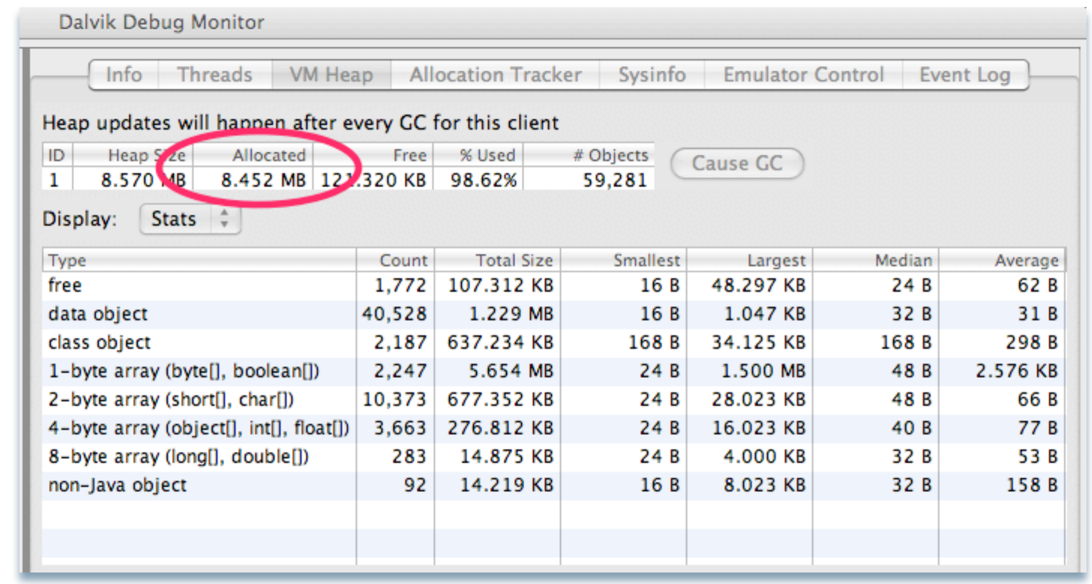
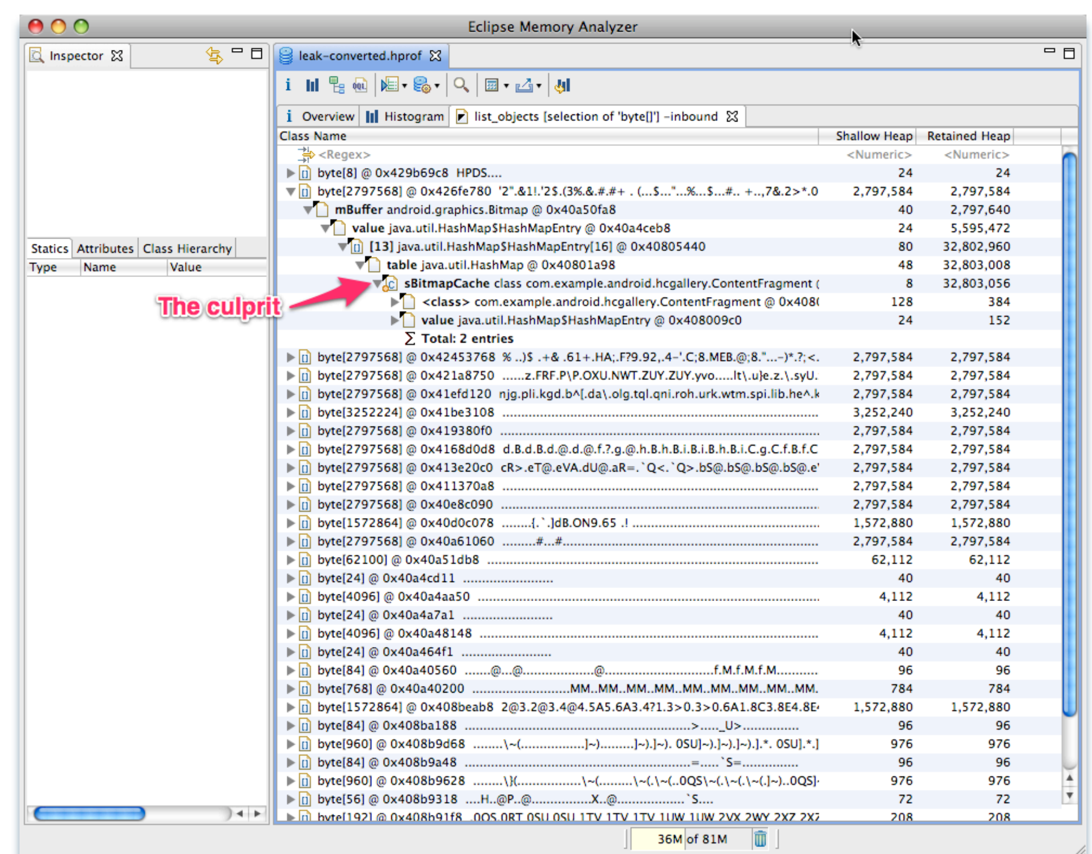


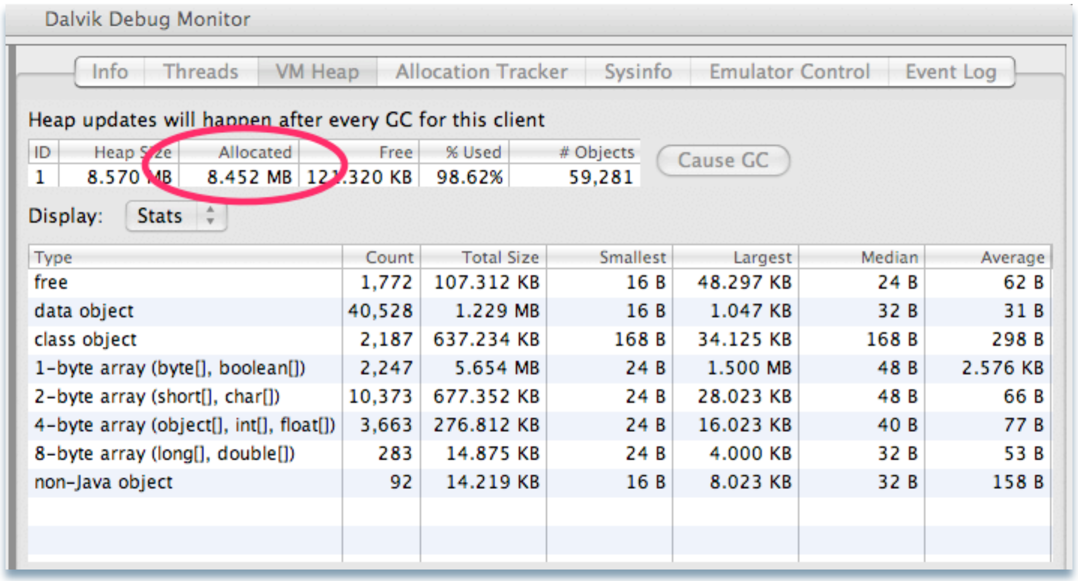

1. Run the app
2. Watch the heap usage
3. Dump the heap. Dig around and **hope** to find the culprit

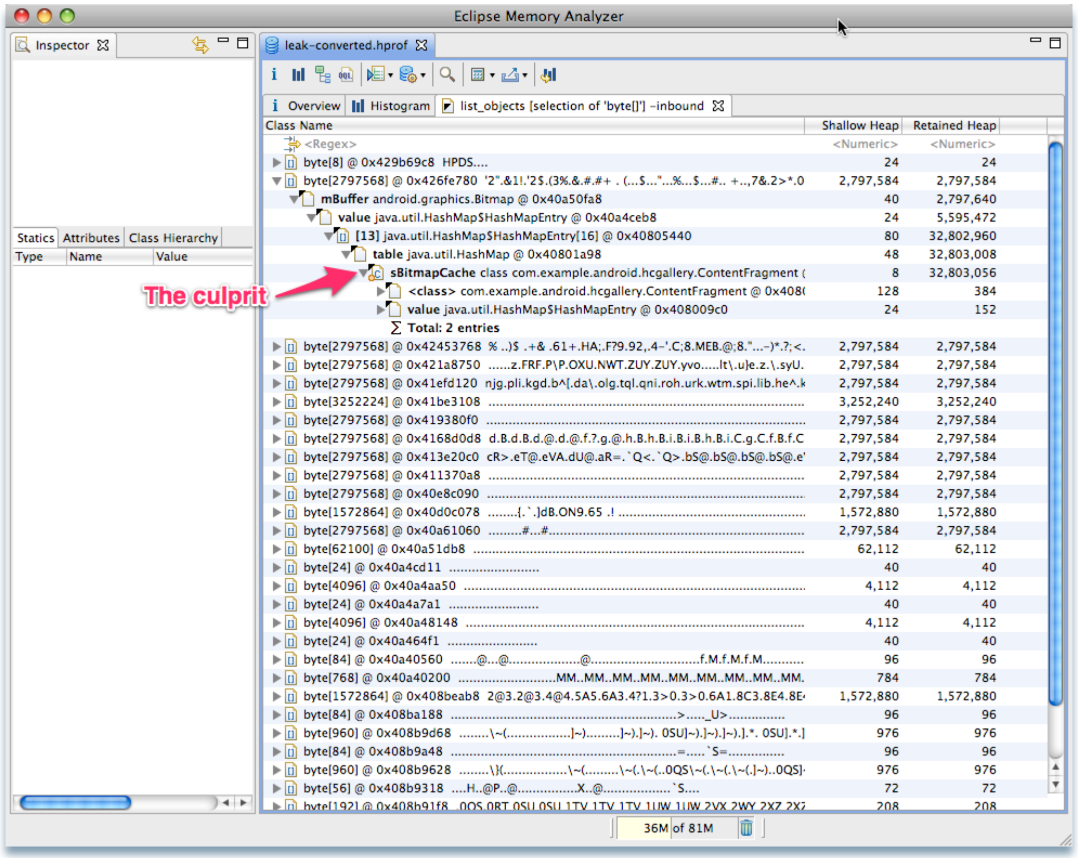
# The state of practice in debugging `Activity` leaks ...

Suppose we're lucky and find a possible culprit. Now what?

- Where in the code is this object allocated?
- What about the object that references it?
- Where is the reference created?
- Is this reference needed?
- For what periods?

3. Dump the heap. Dig around and hope to find the culprit



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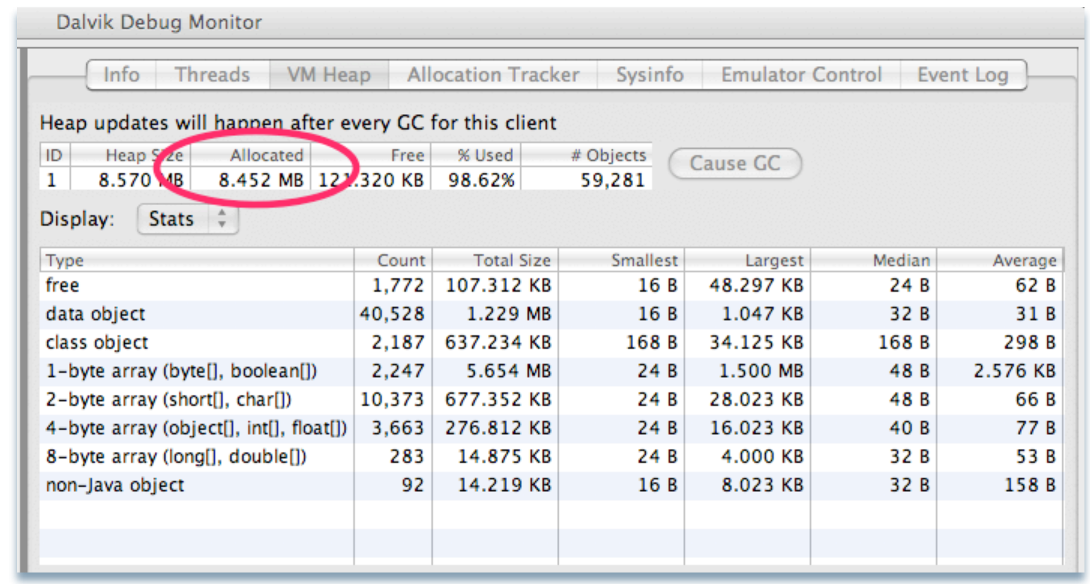
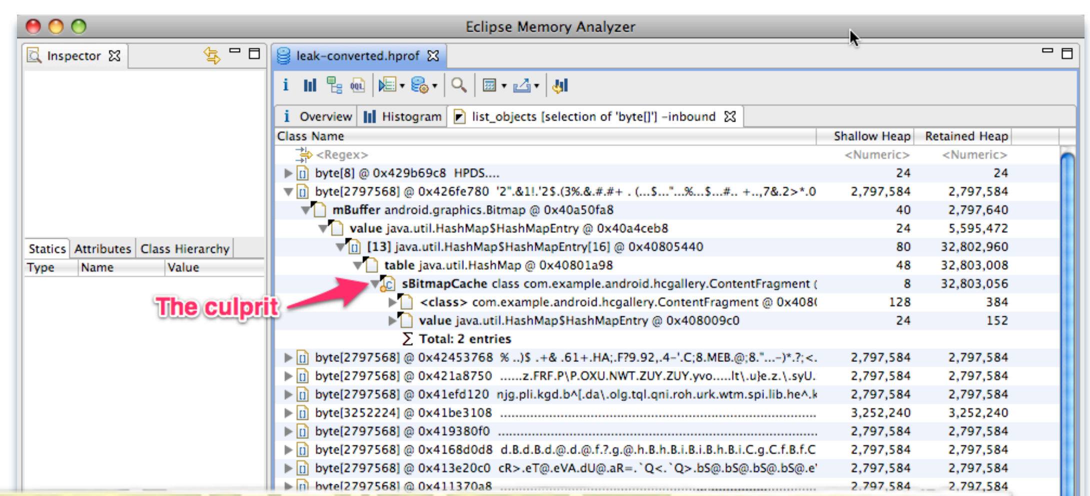



3. Dump the heap. Dig

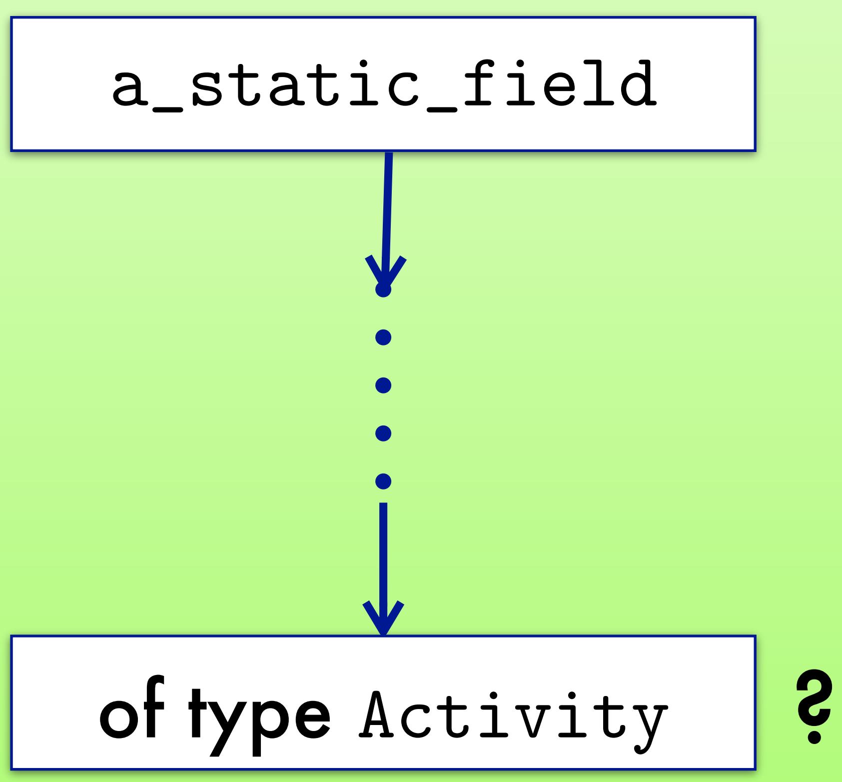
"One of the most dreaded bugs in Android is a memory leak. They are nasty because one piece of code causes an issue and in some other piece of code, your application crashes." – http://therockncoder.blogspot.com/2012/09/fixing-android-memory-leak.html


Program
Analysis

# Answering “Is there an `Activity` leak?” with program analysis …

Can an object ever be reached from another object via pointer dereferences?

Is there a program execution where at some time

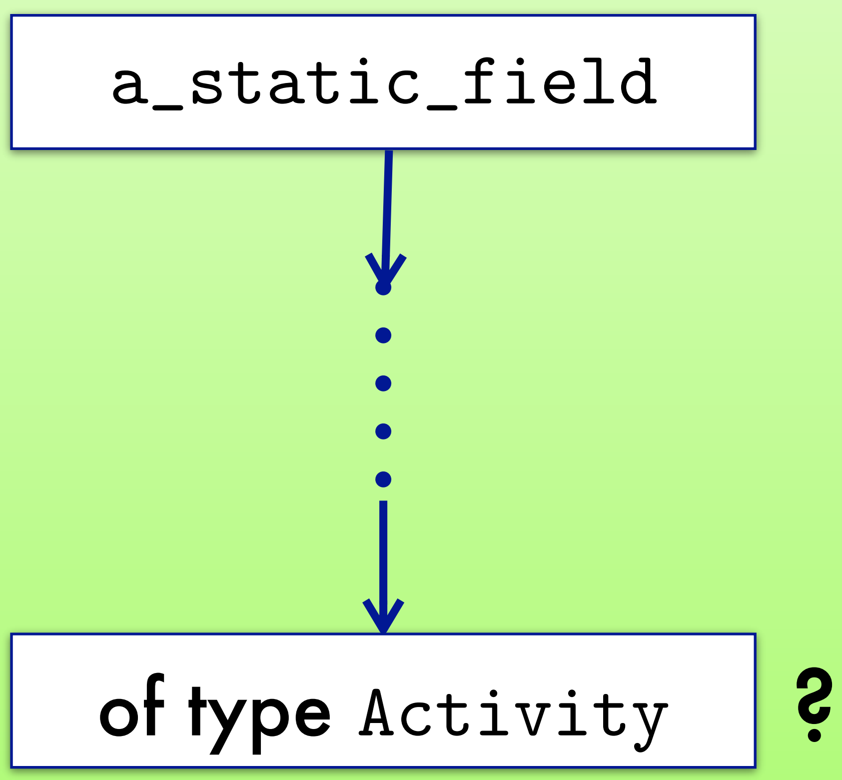



Example

# Answering "Is there an `Activity` leak?" with program analysis ...

Can an object ever be reached from another object via pointer dereferences?

Is there a program execution where at some time




Example

Can be answered with a points-to analysis

# Answering "Is there an `Activity` leak?" with program analysis ...

Can an object ever be reached from another object via pointer dereferences?

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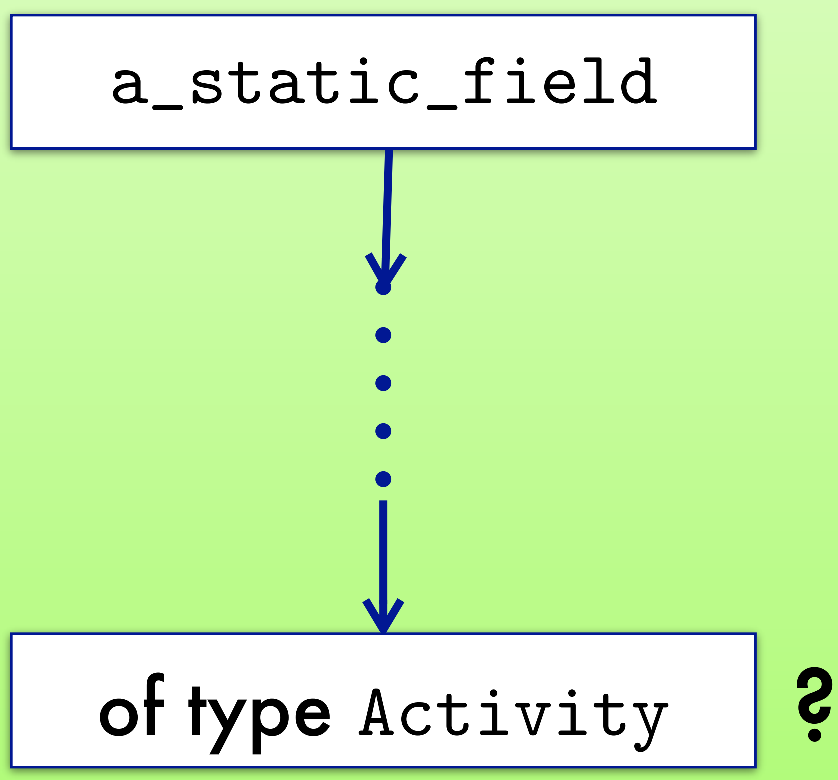



Example

Can be answered with a points-to analysis

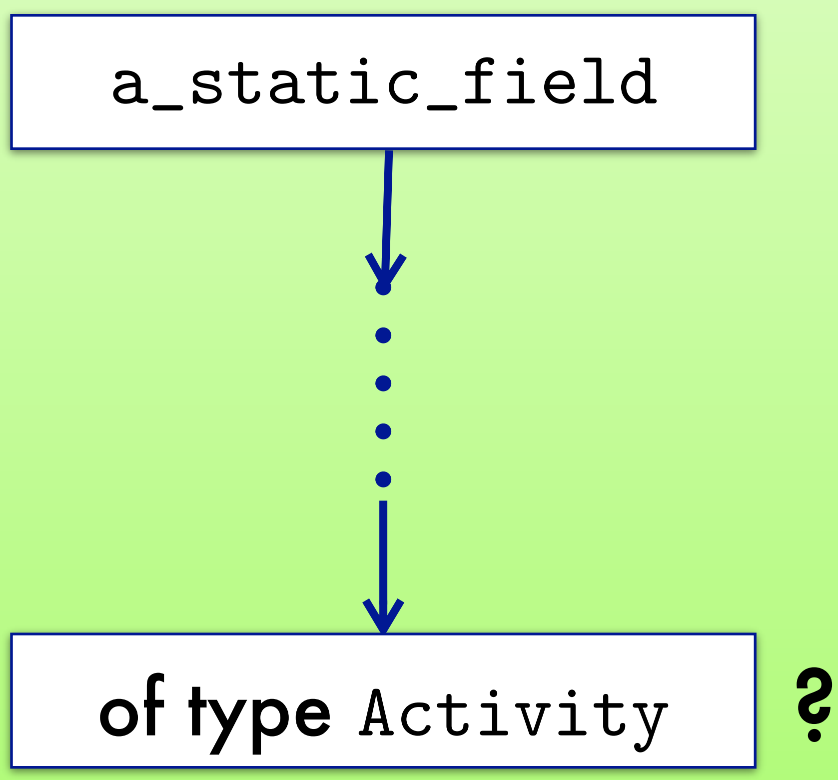
Hidden Truth

with **approximation**

# Answering "Is there an `Activity` leak?" with program analysis ...

Can an object ever be reached from another object via pointer dereferences?

Is there a program execution where at some time




Example

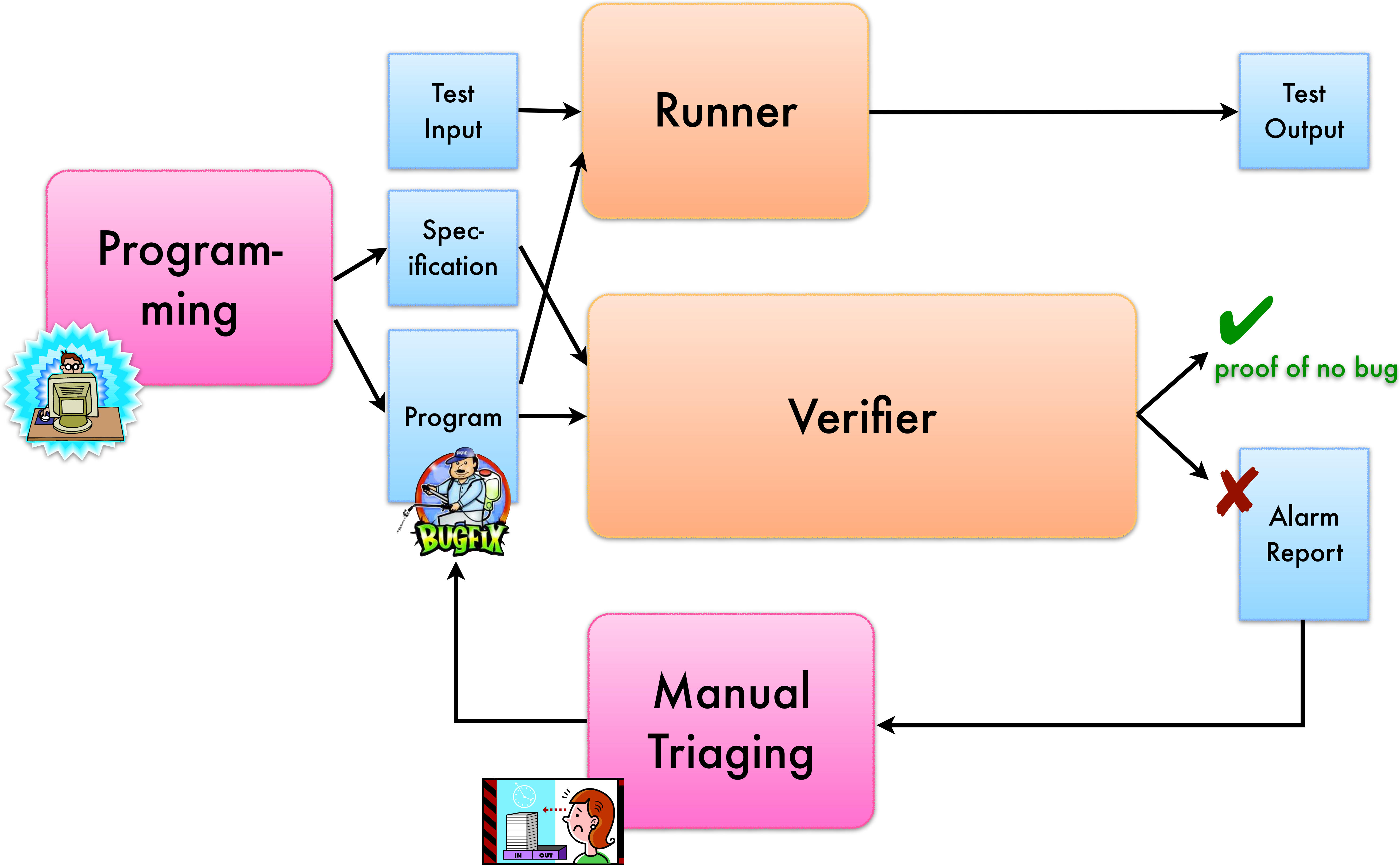
Can be answered with a points-to analysis

Hidden Truth

with **approximation**

Some pointer relations **may** be false

# But with the cooperative approach ...



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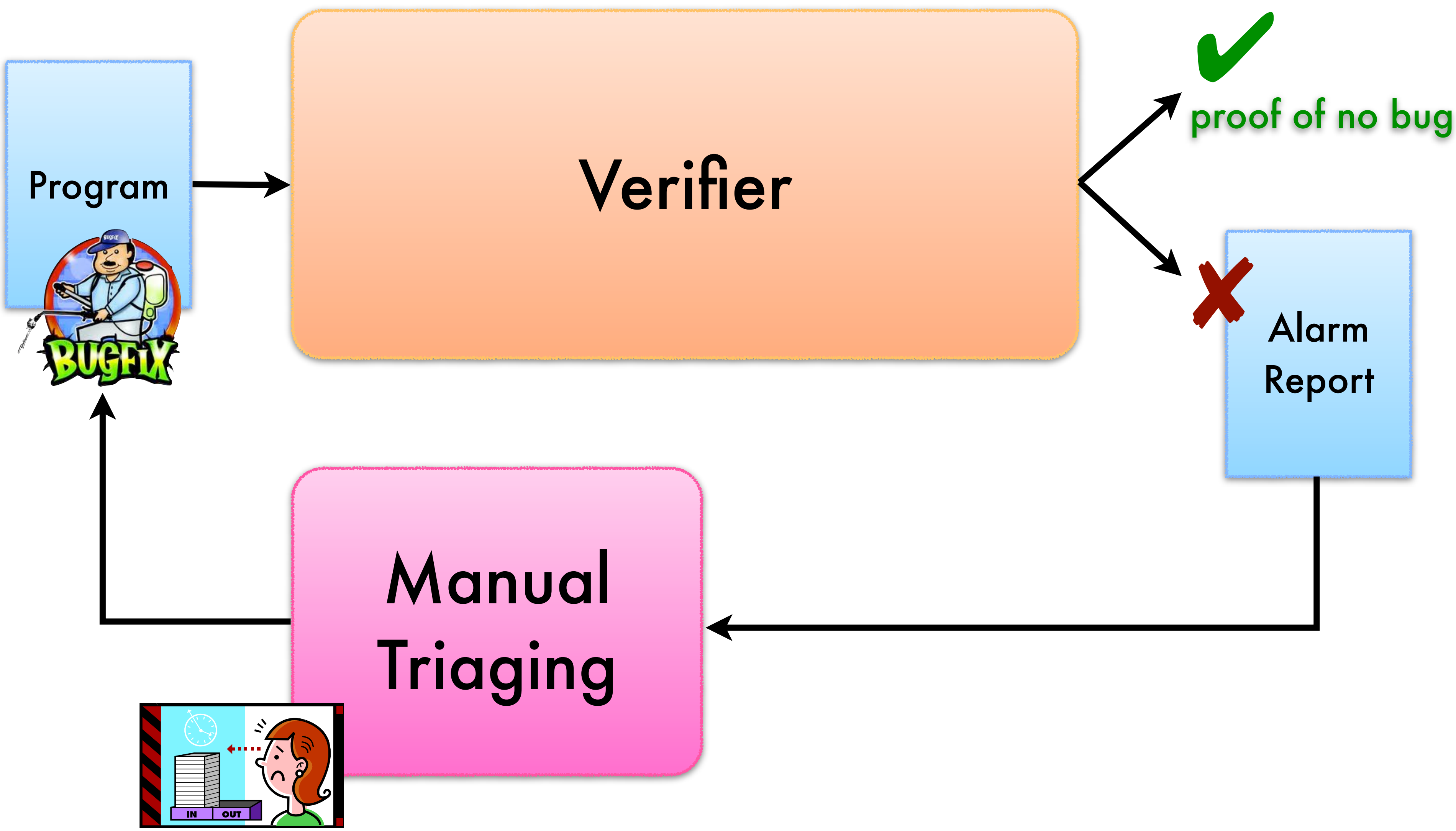
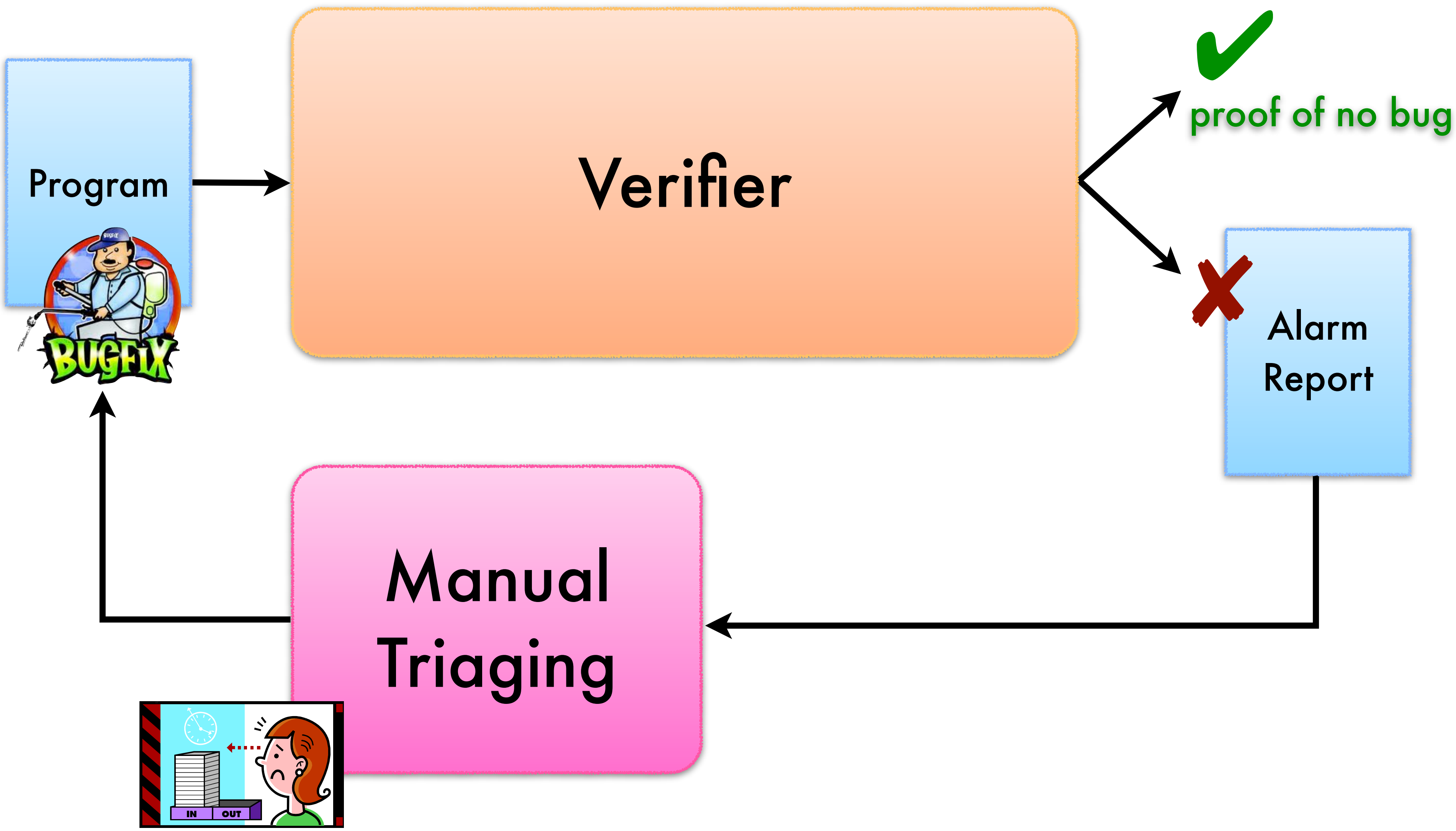


# Thresher addresses alarm **triage** in a particularly challenging domain.



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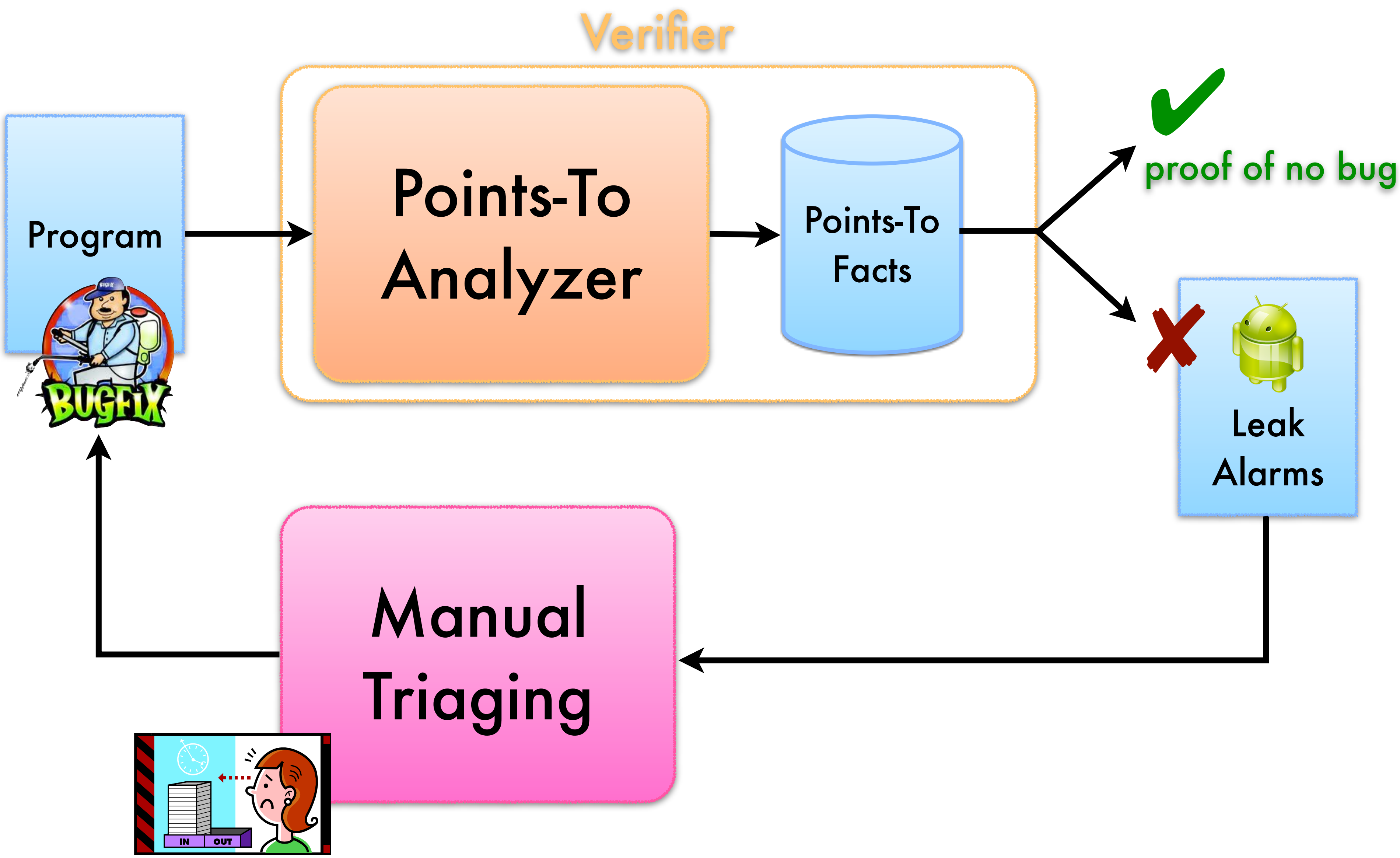

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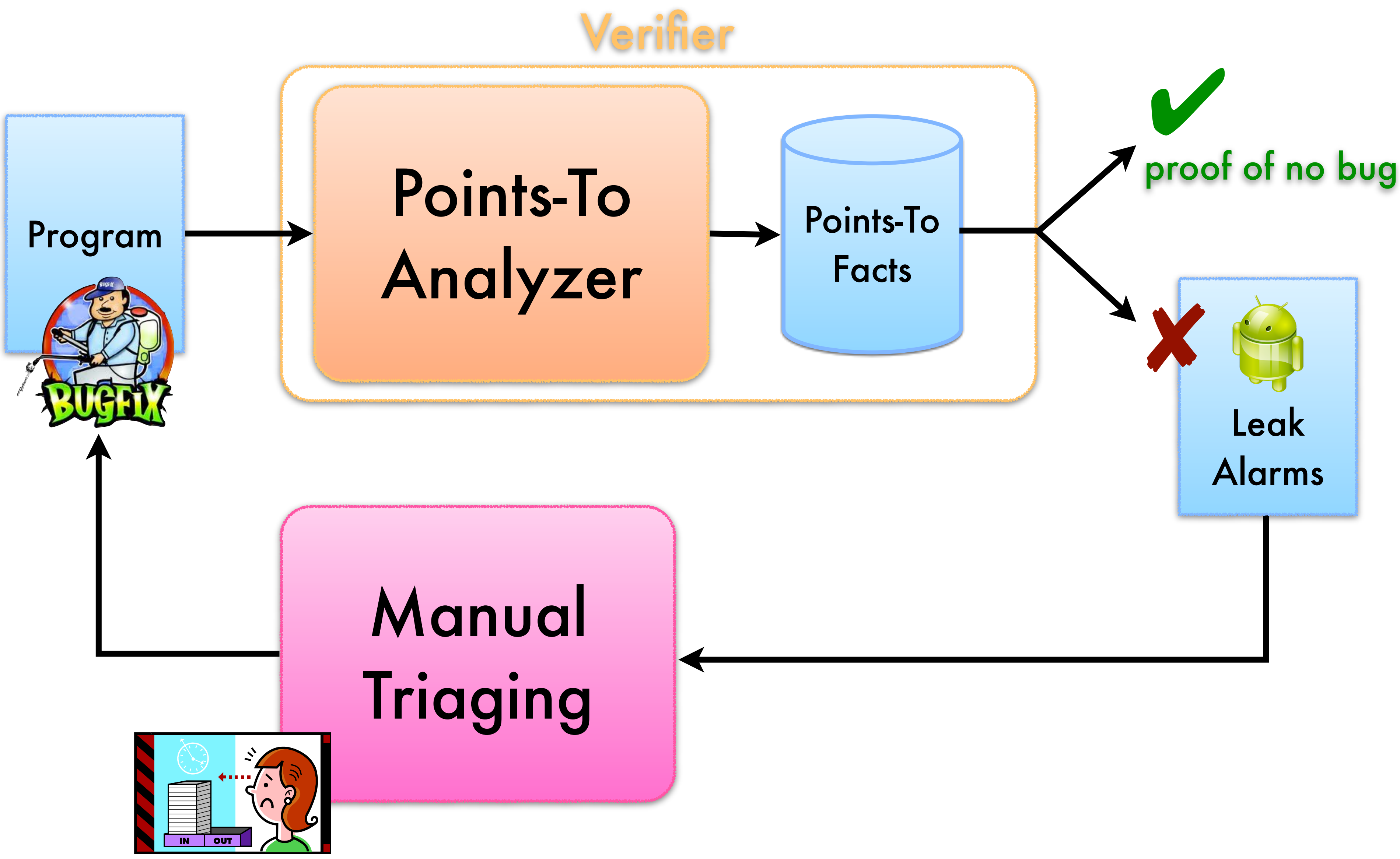
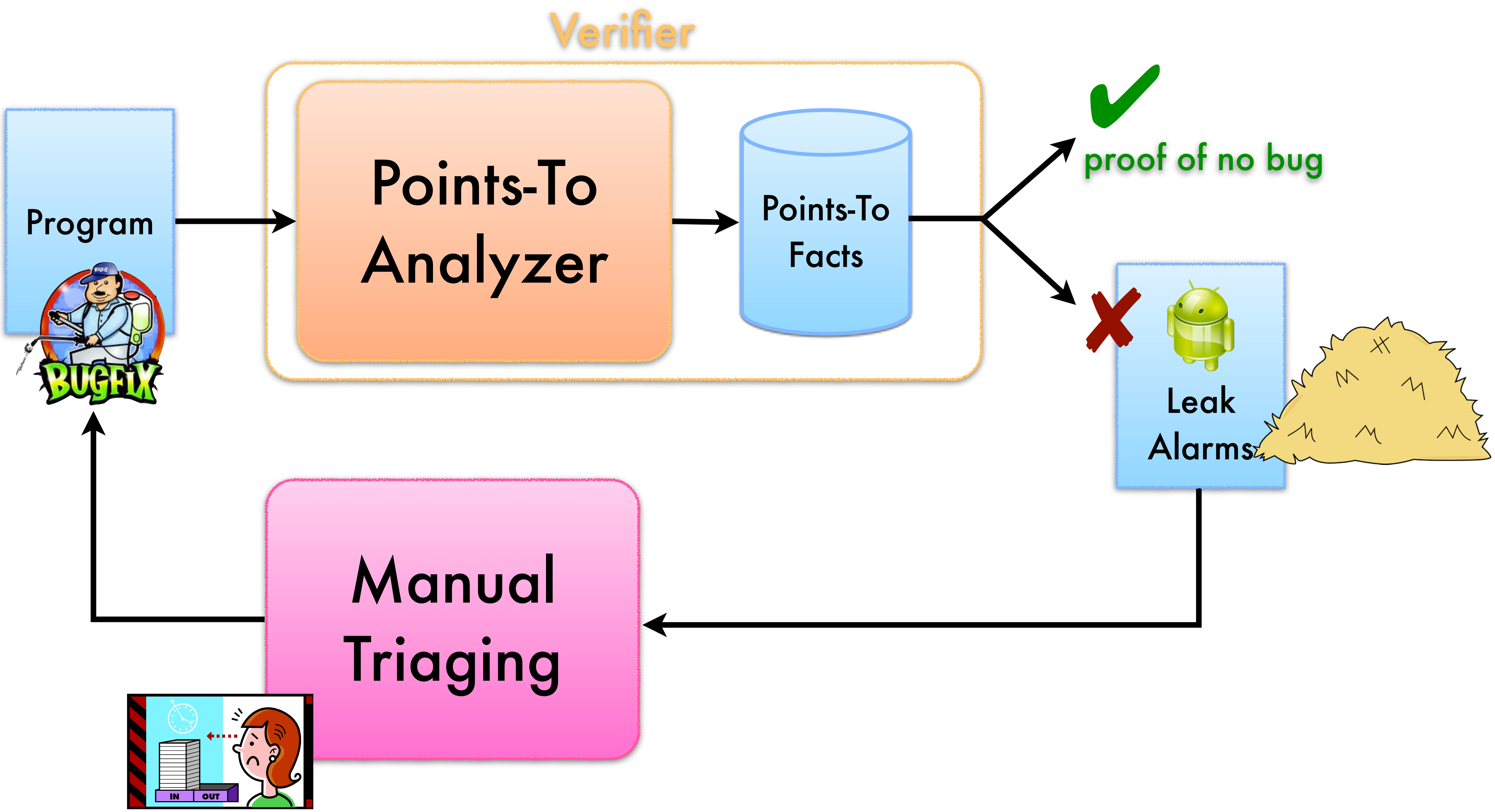



Known: Precise points-to analysis challenging

# Thresher addresses alarm **triage** in a particularly challenging domain.

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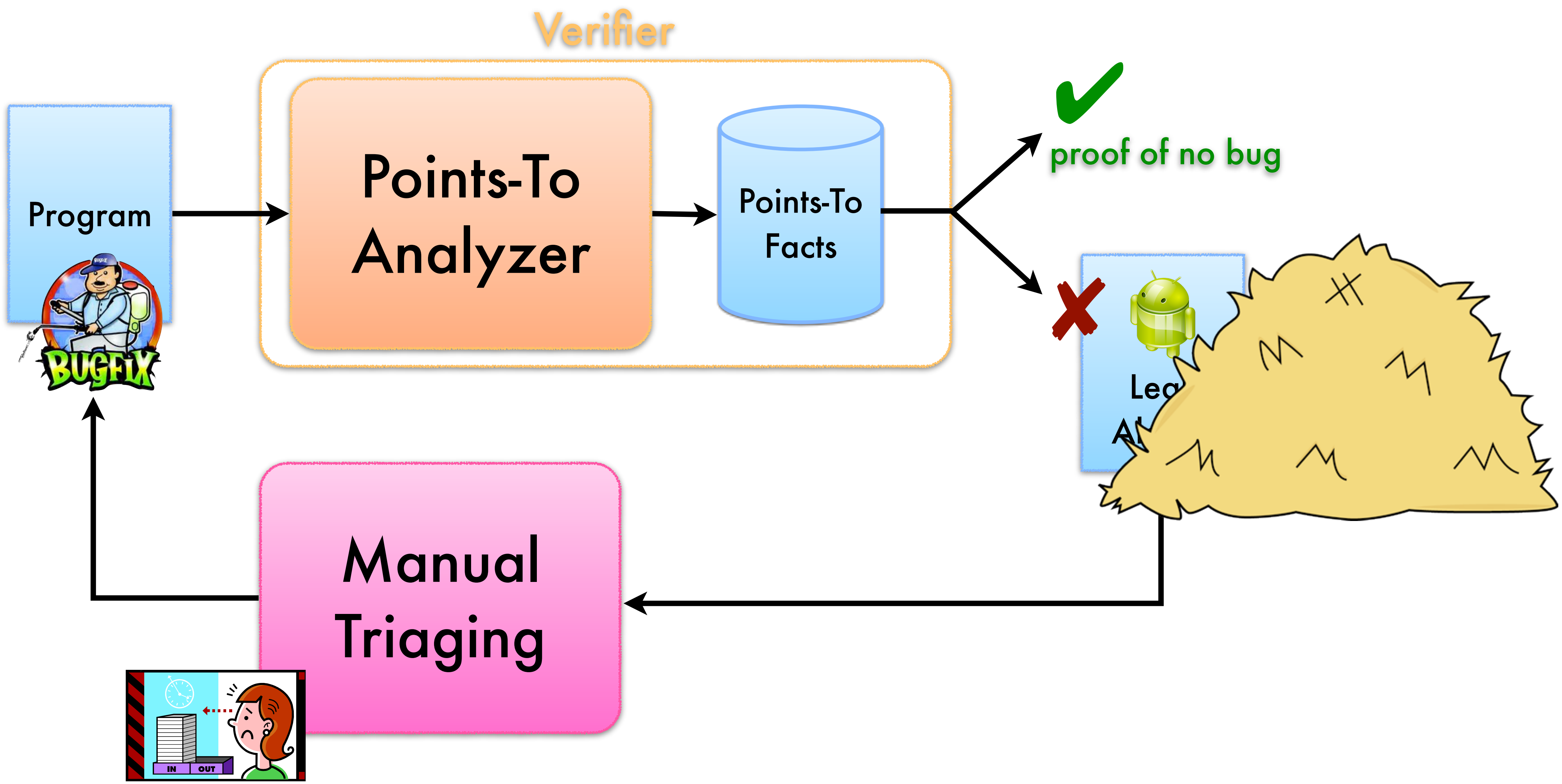


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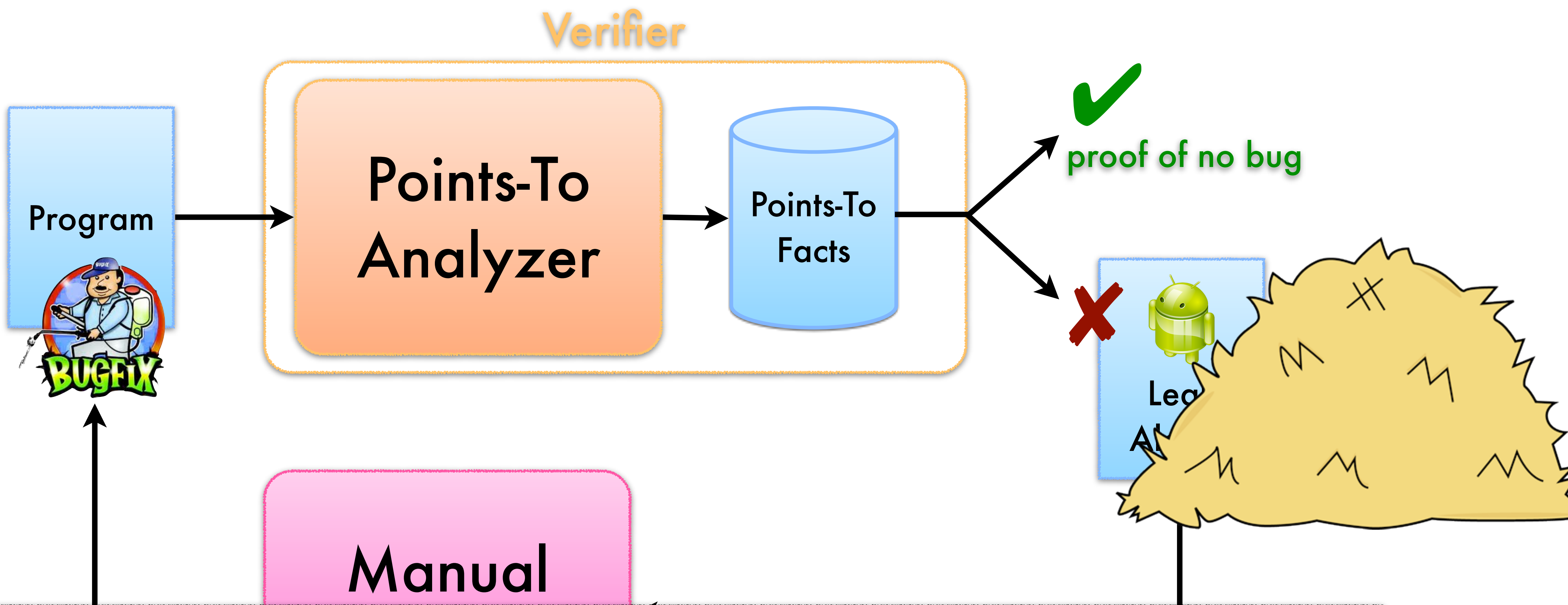


Hind. “Pointer Analysis: Haven’t We Solved This Problem Yet?”

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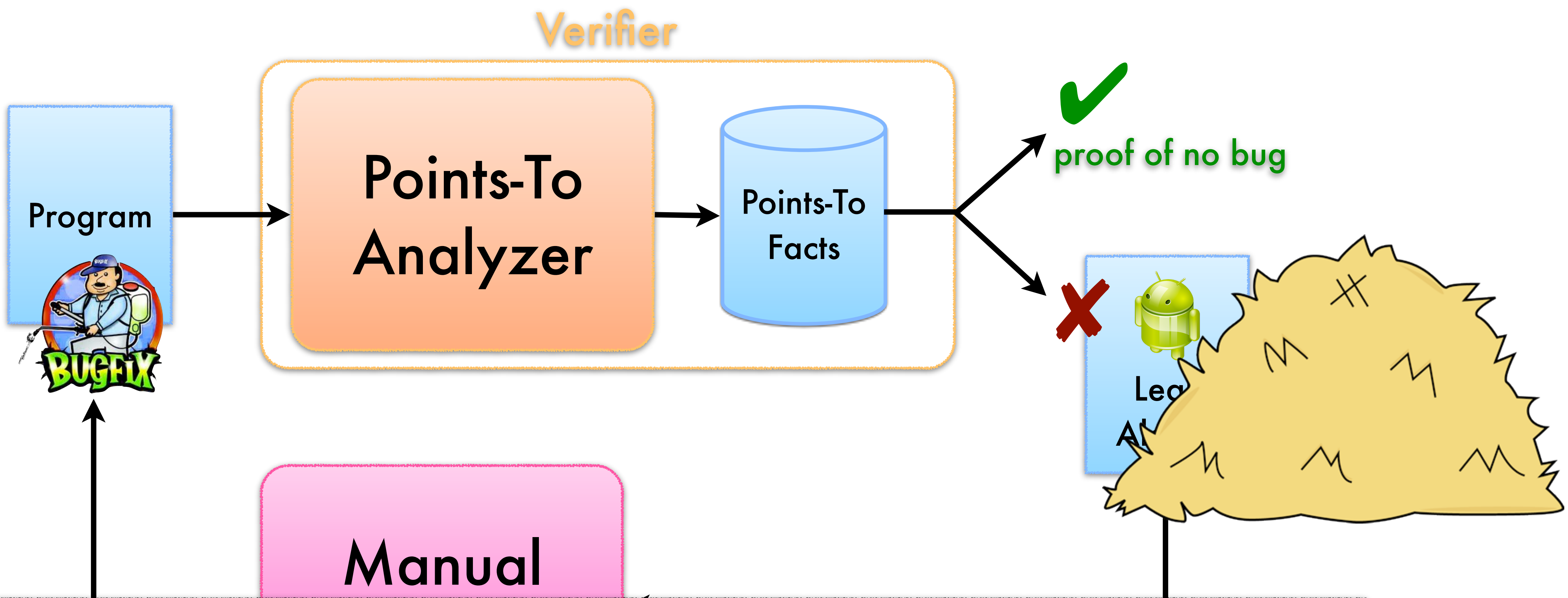


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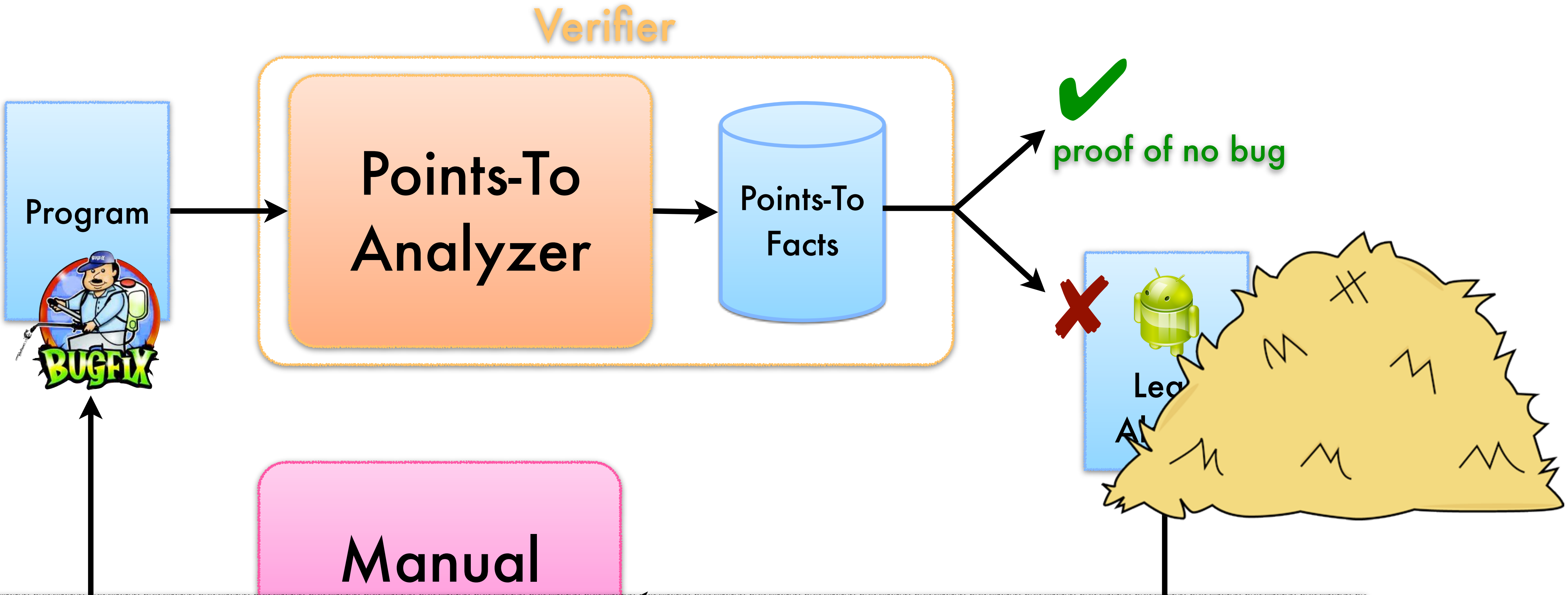


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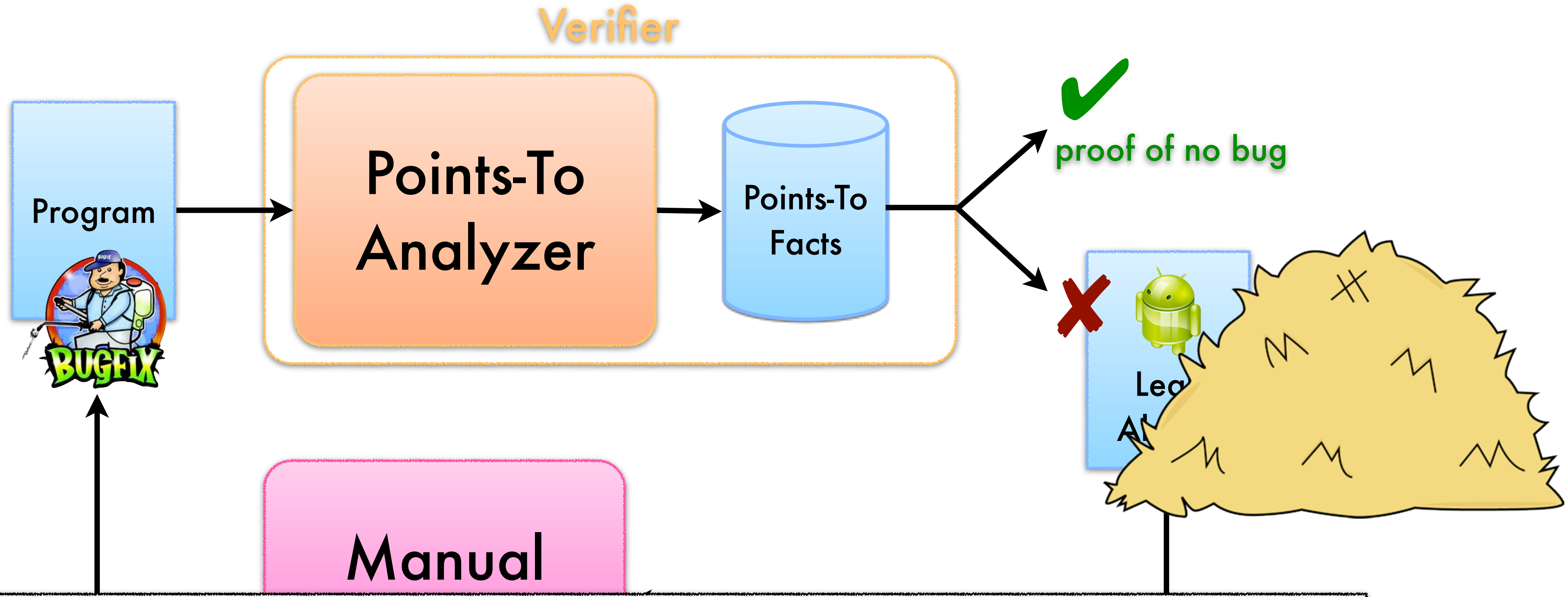


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Dagstuhl 13162: Pointer Analysis (2013)

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

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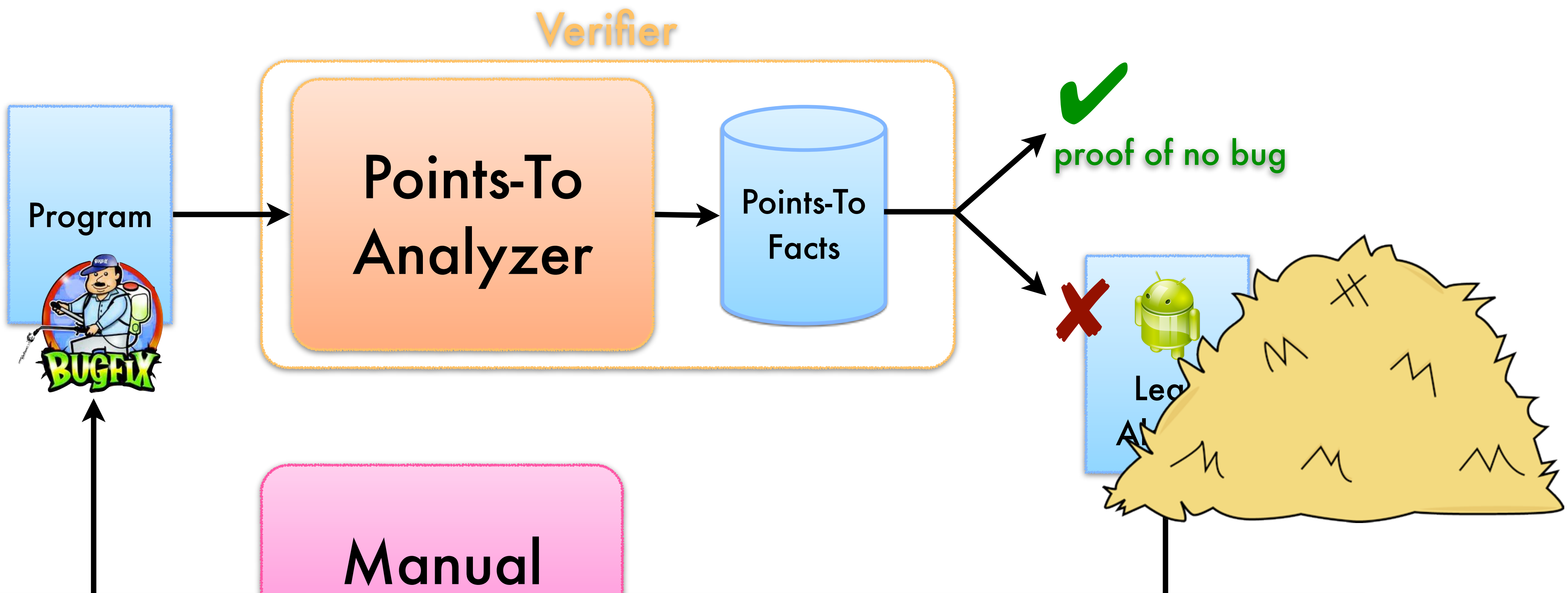


Hind. "Pointer Analysis: Haven't We Solved This Problem Yet?" (2001)

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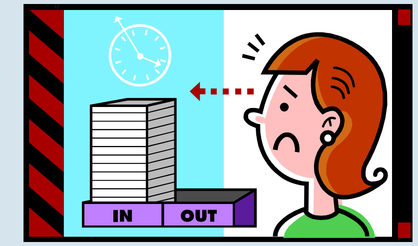
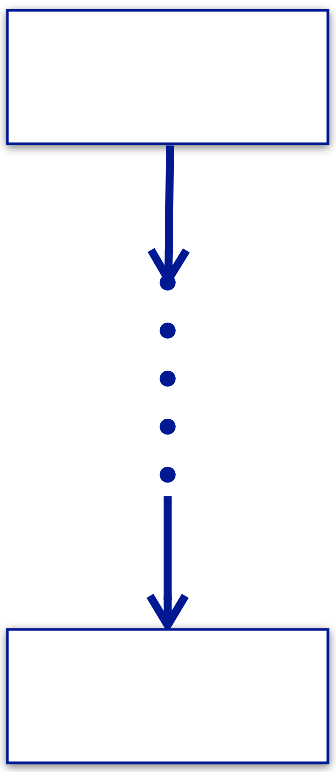
Dagstuhl 13162: Pointer Analysis (2013)

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

# Manual triage is particularly hard for heap reachability reports.



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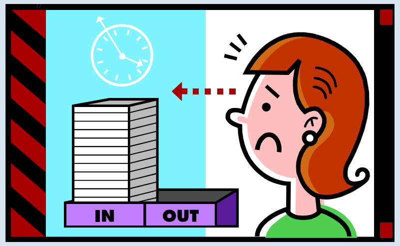


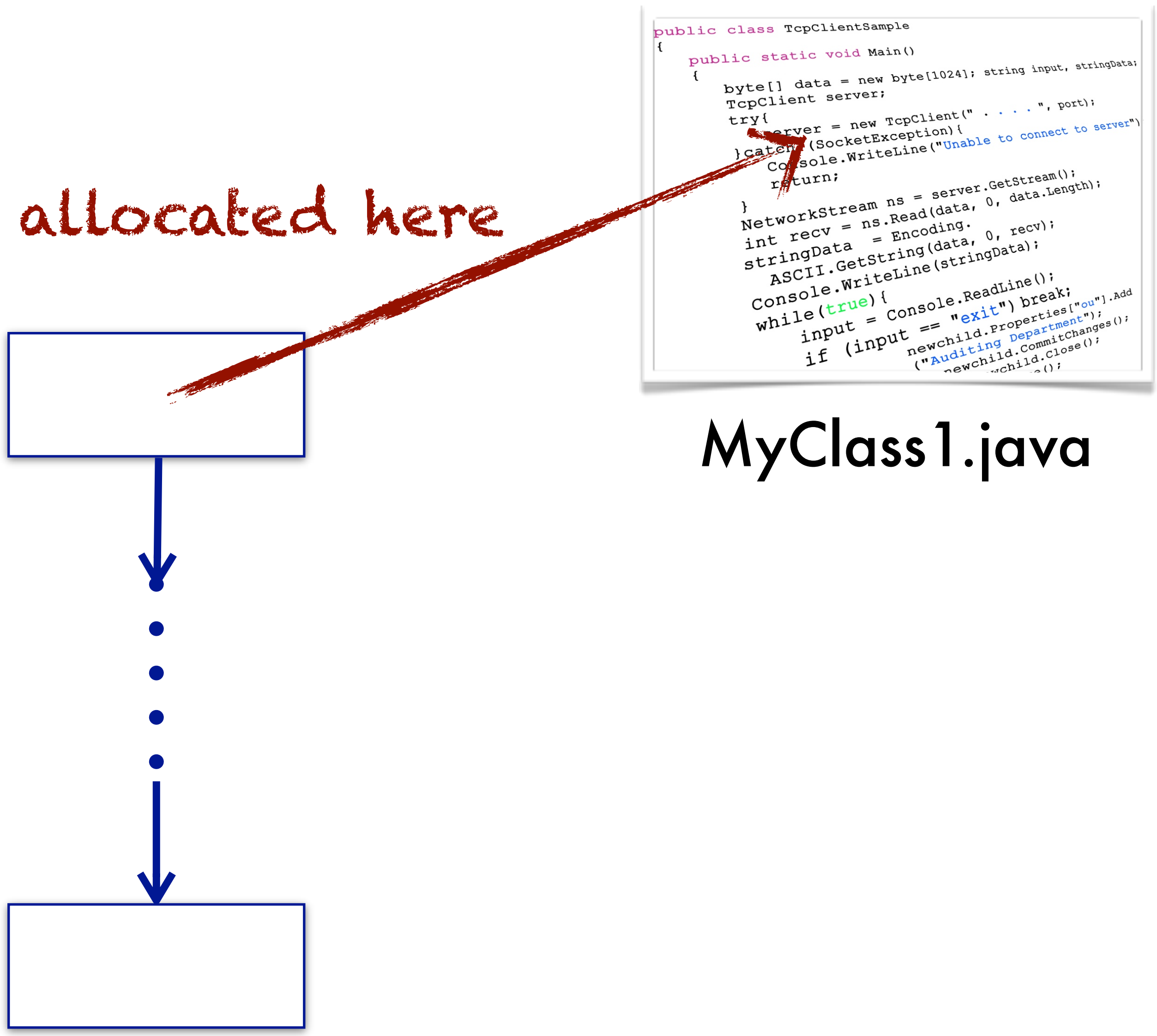

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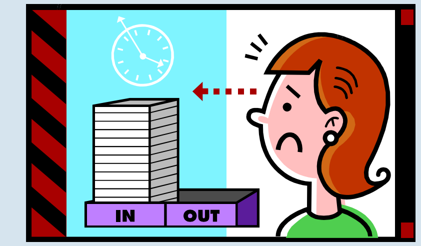

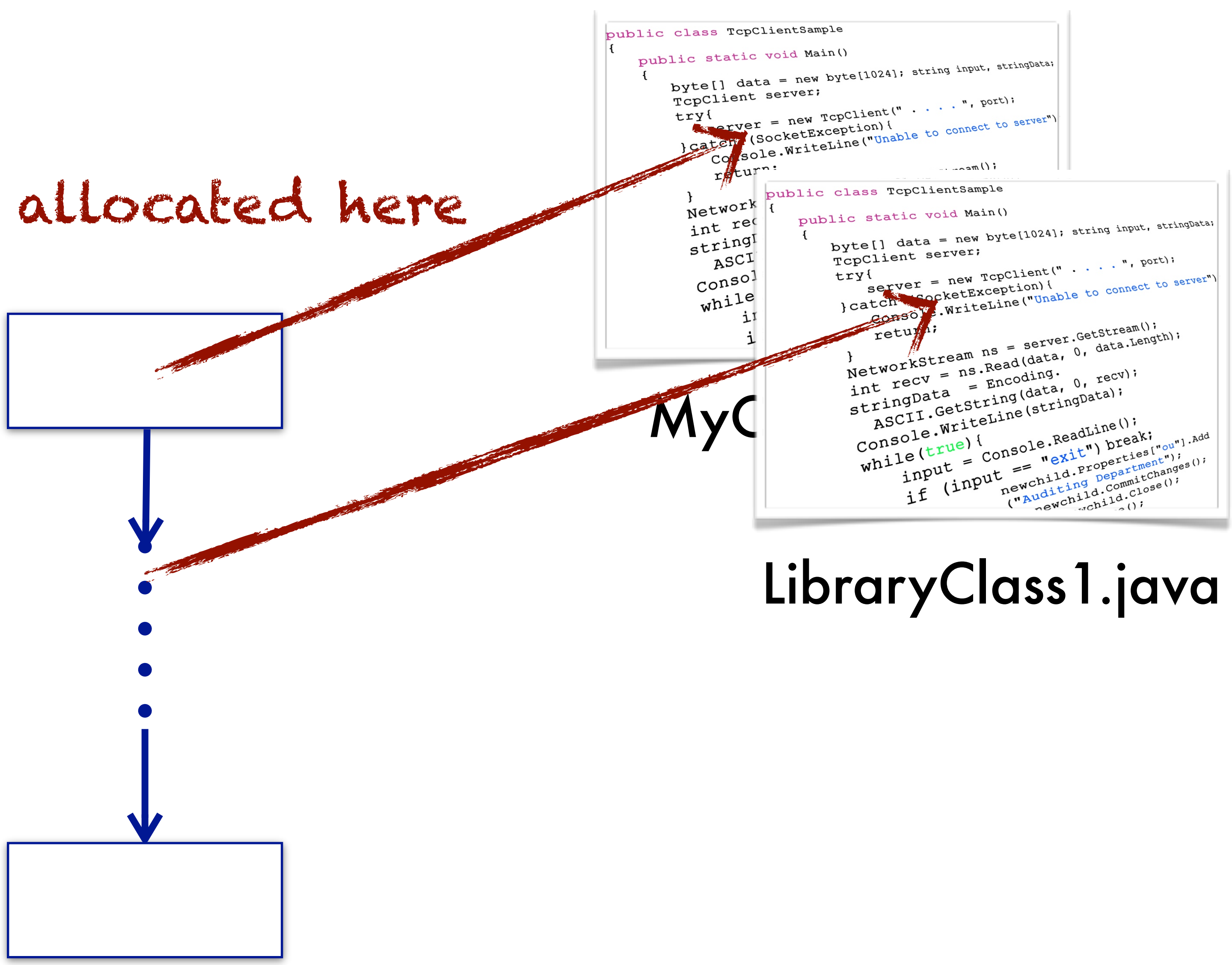

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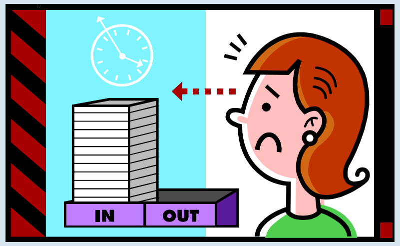

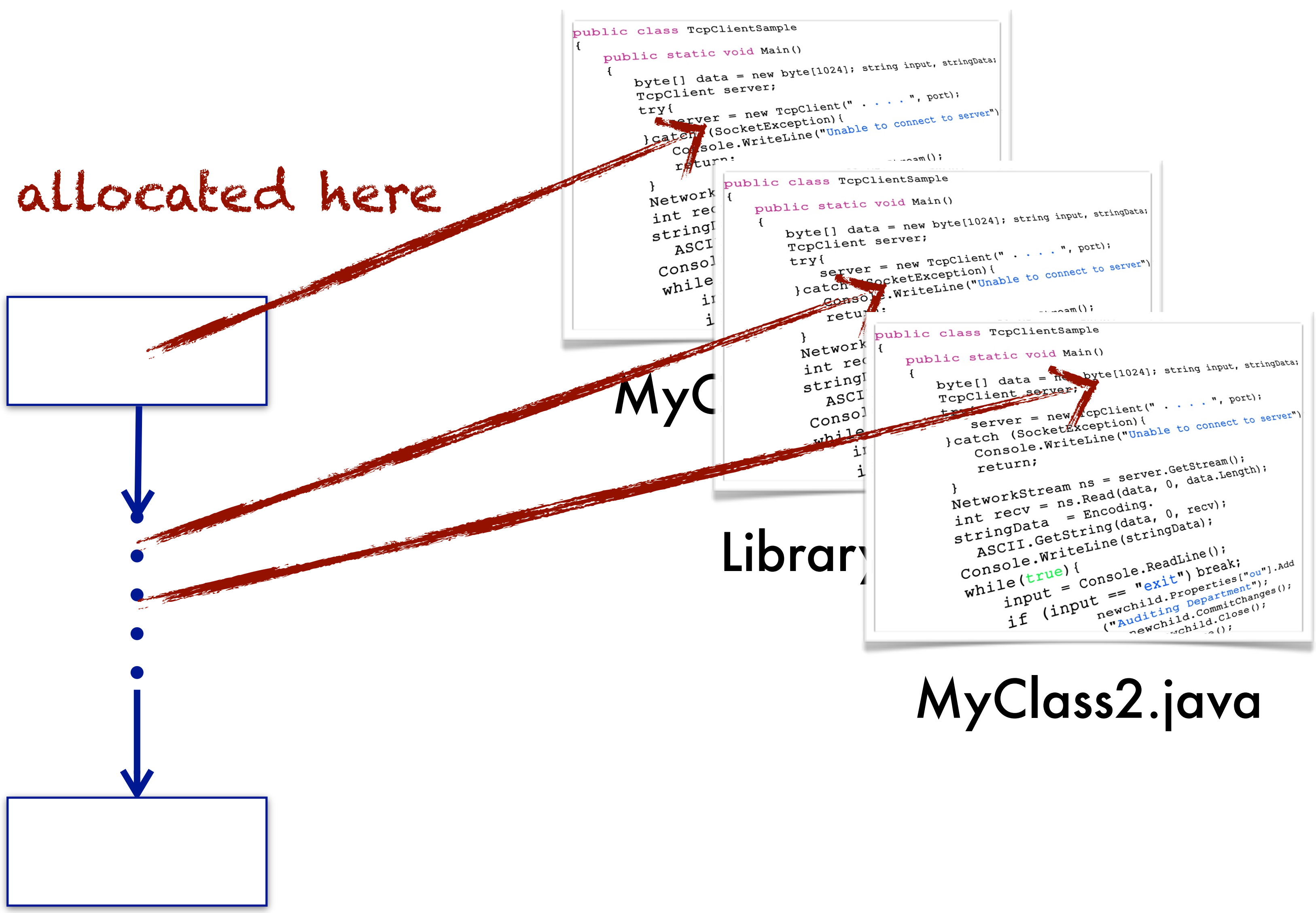

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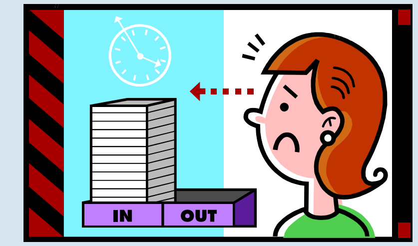

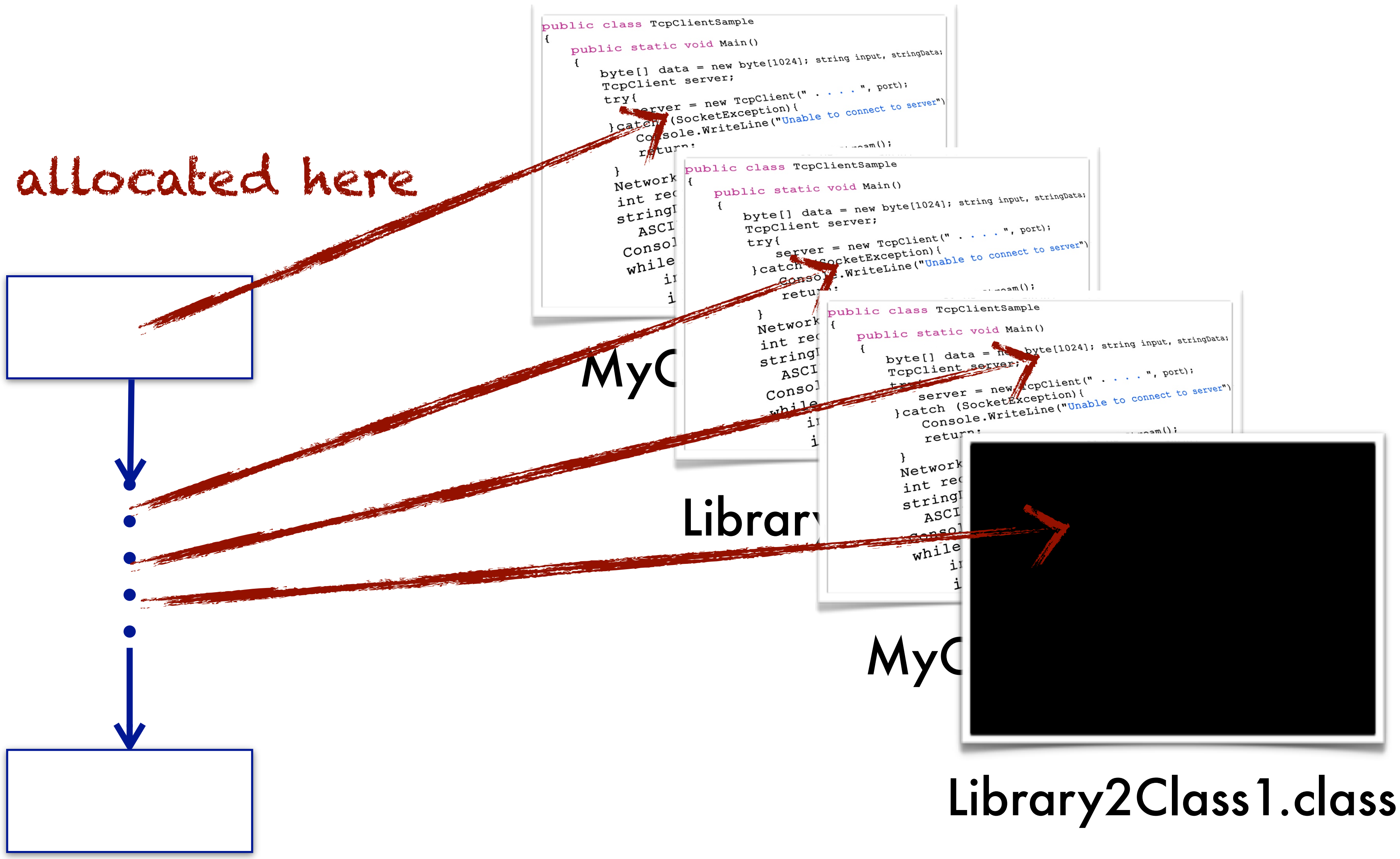

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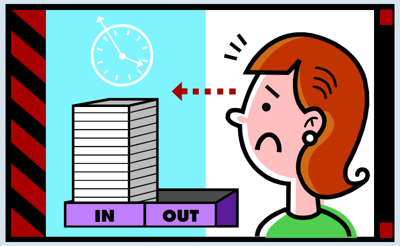


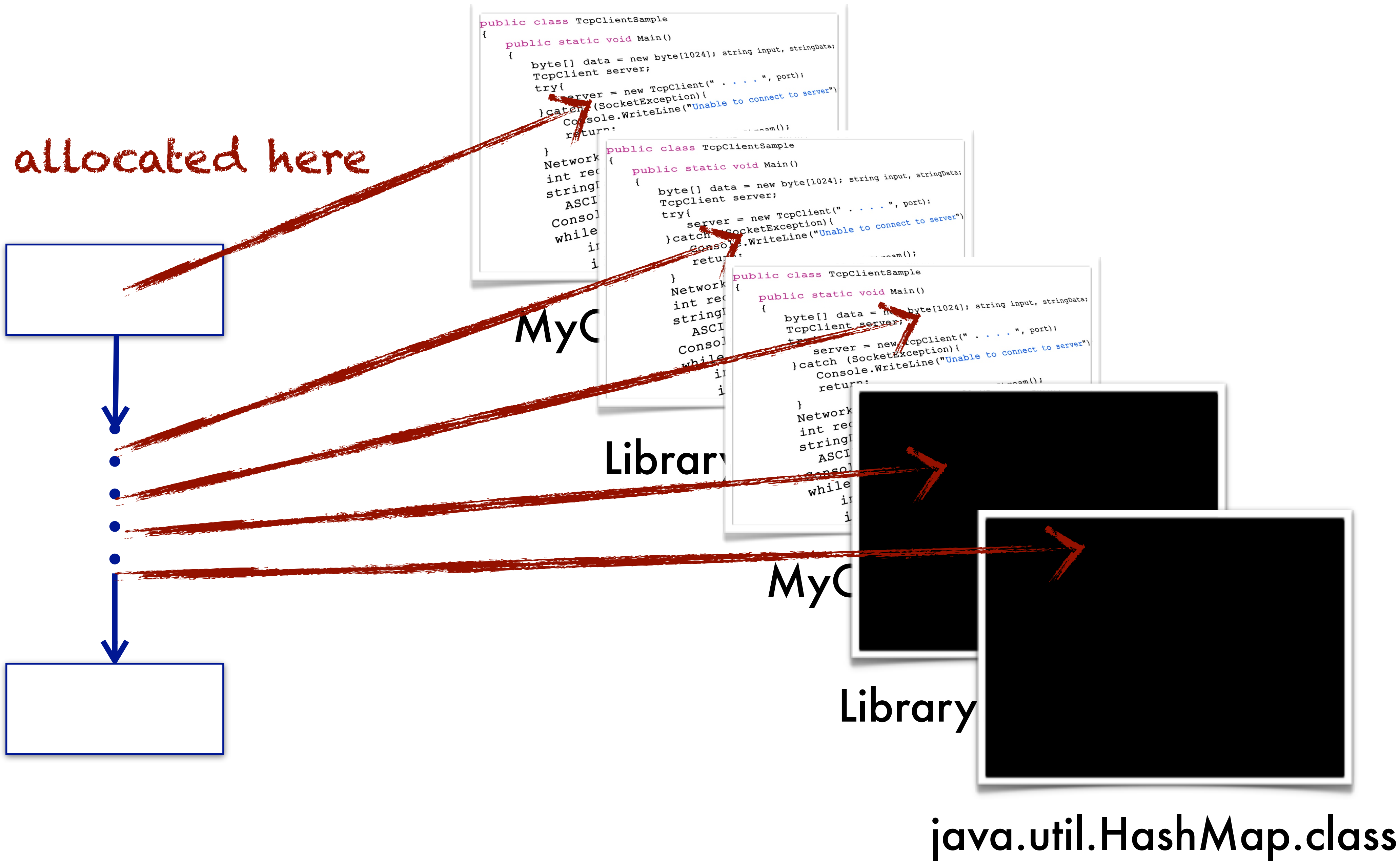

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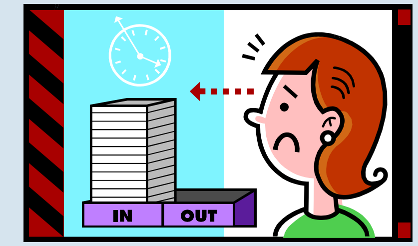

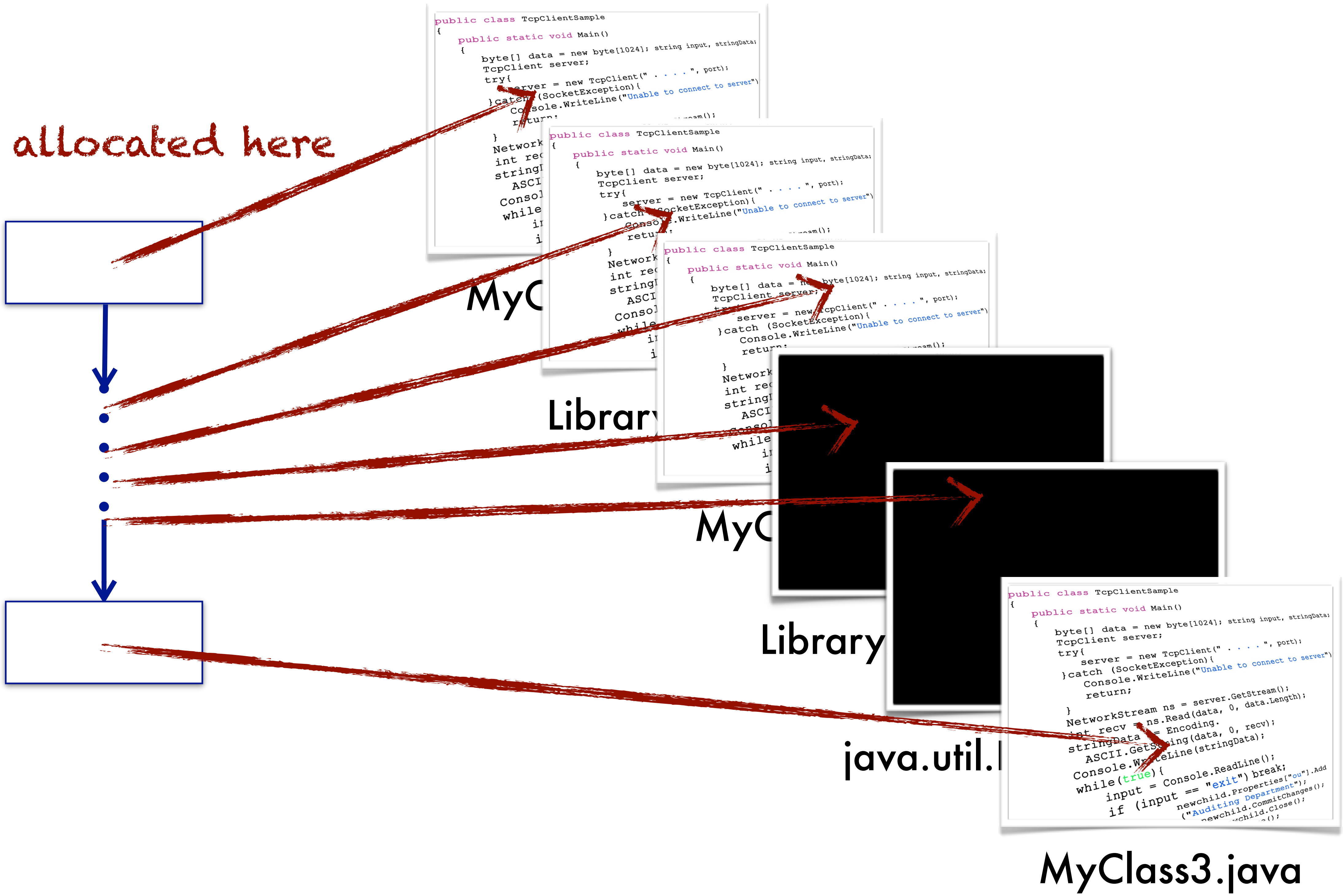

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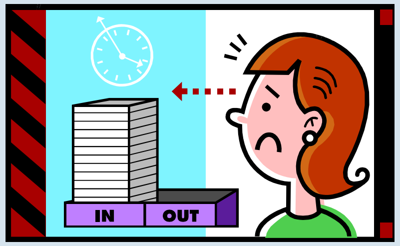
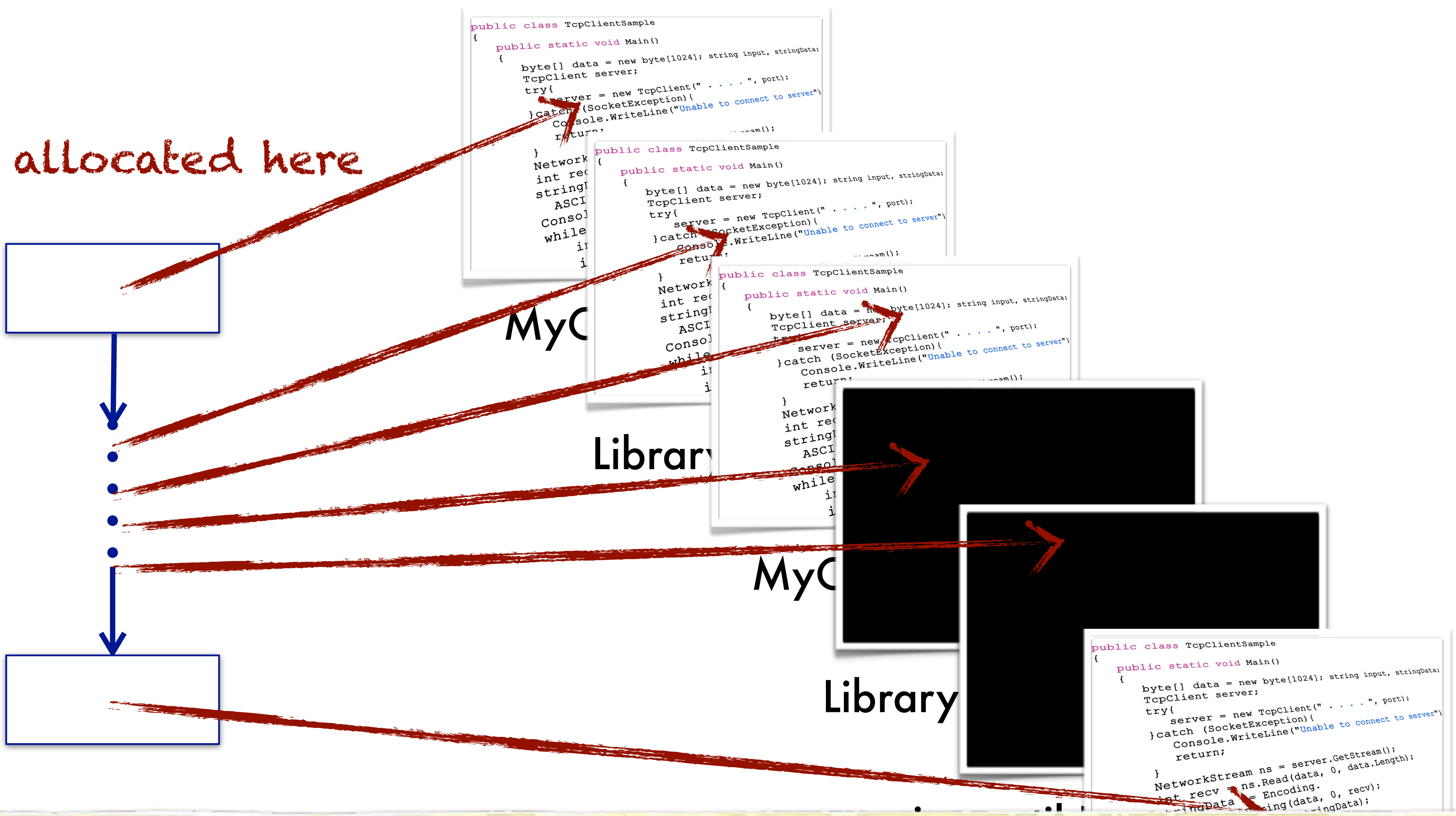
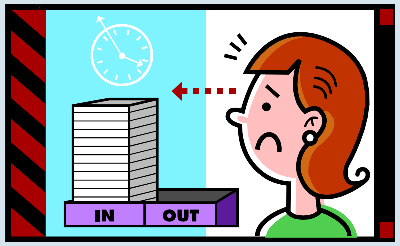



Get abstract heap path + maybe allocation sites
Guesstimate: >1 to 2 hours per alarm to triage “well”

# Examining manual triage ...



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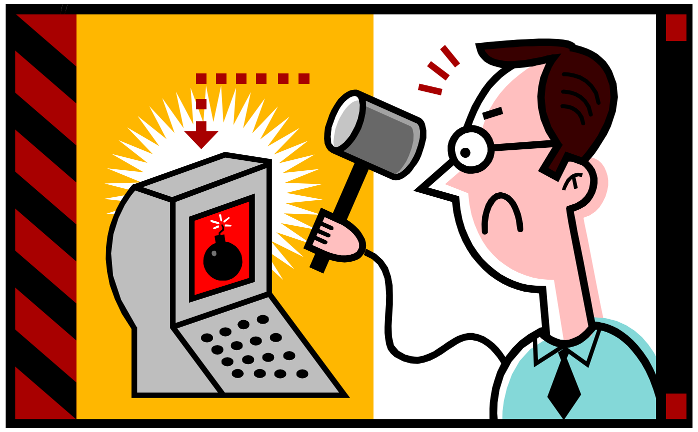

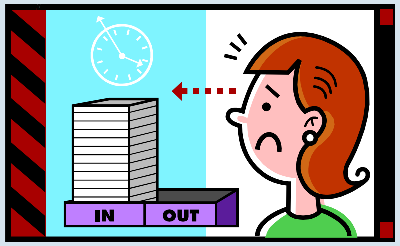

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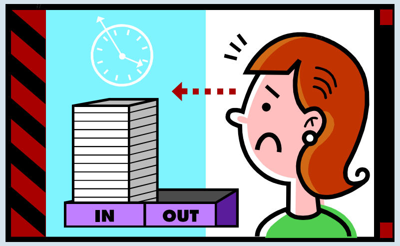


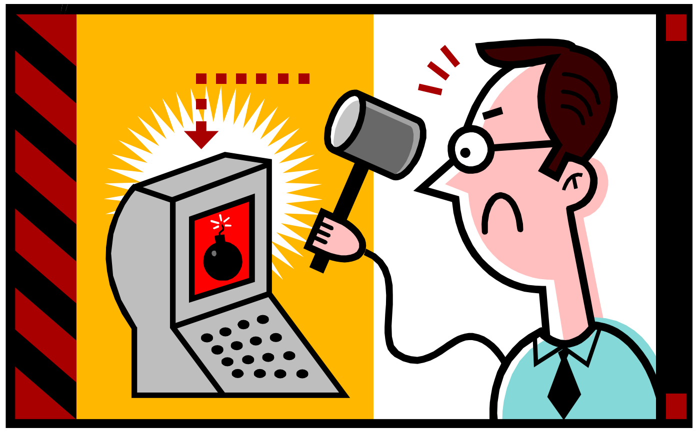

What does the user need to do with an alarm? He starts at, say, line 142 and traces back to see if a bug is possible given what's happening.

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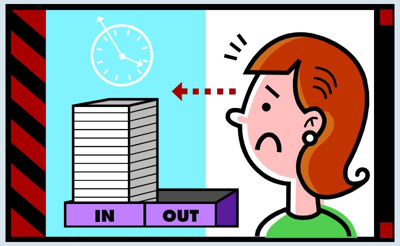


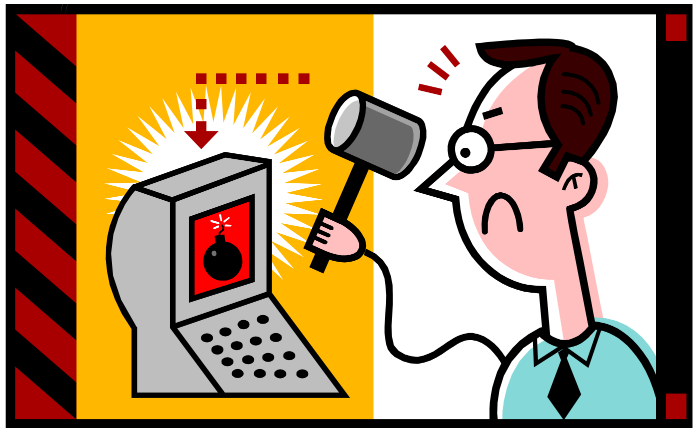

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We can do this with analysis!

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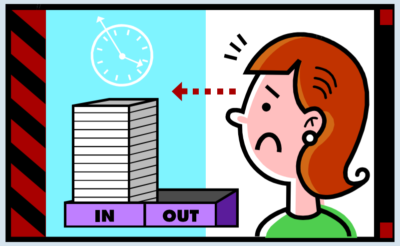


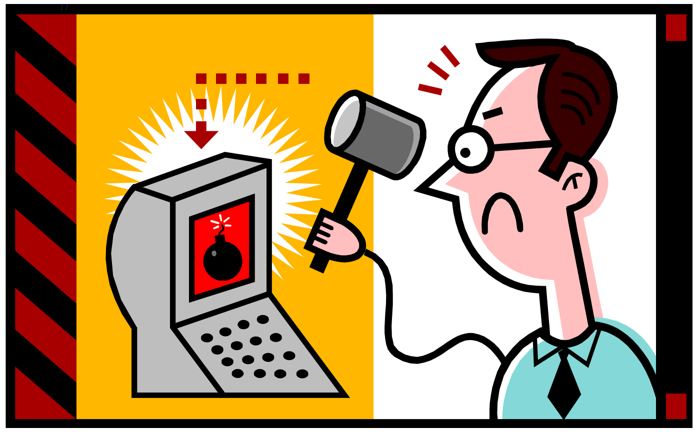

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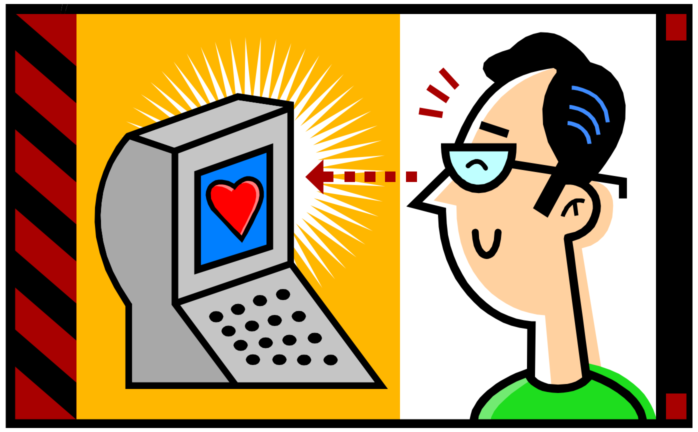

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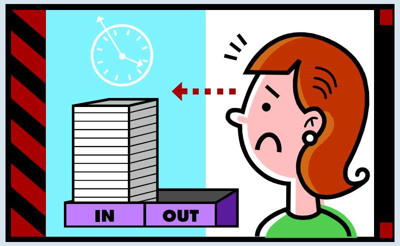


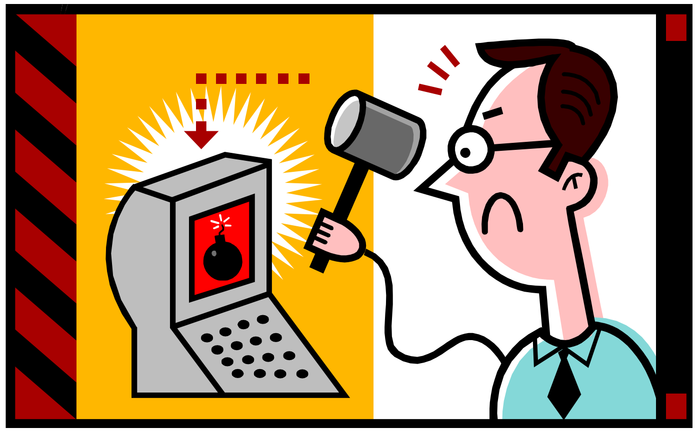

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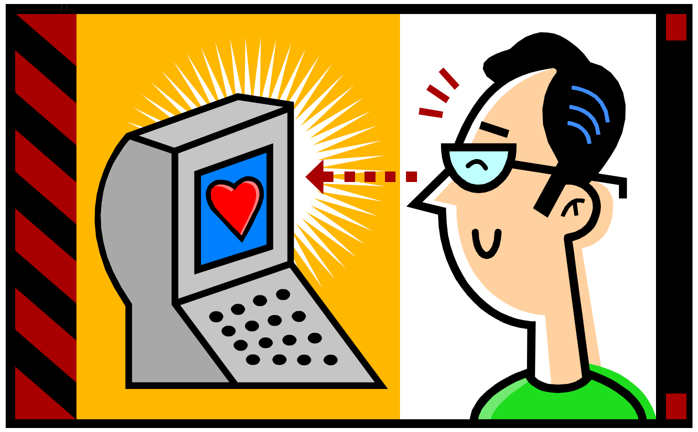
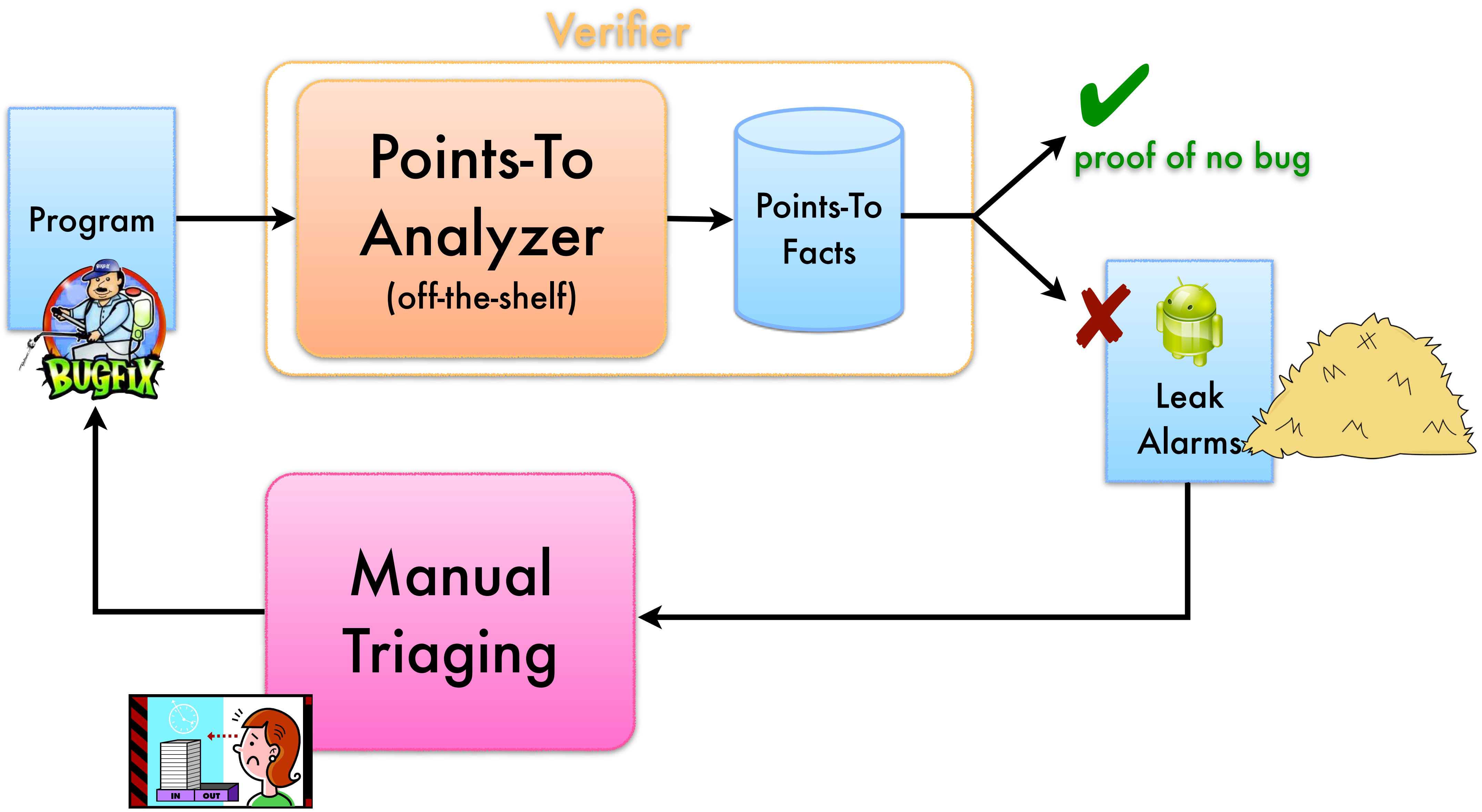
**We can do this with analysis!**



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

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



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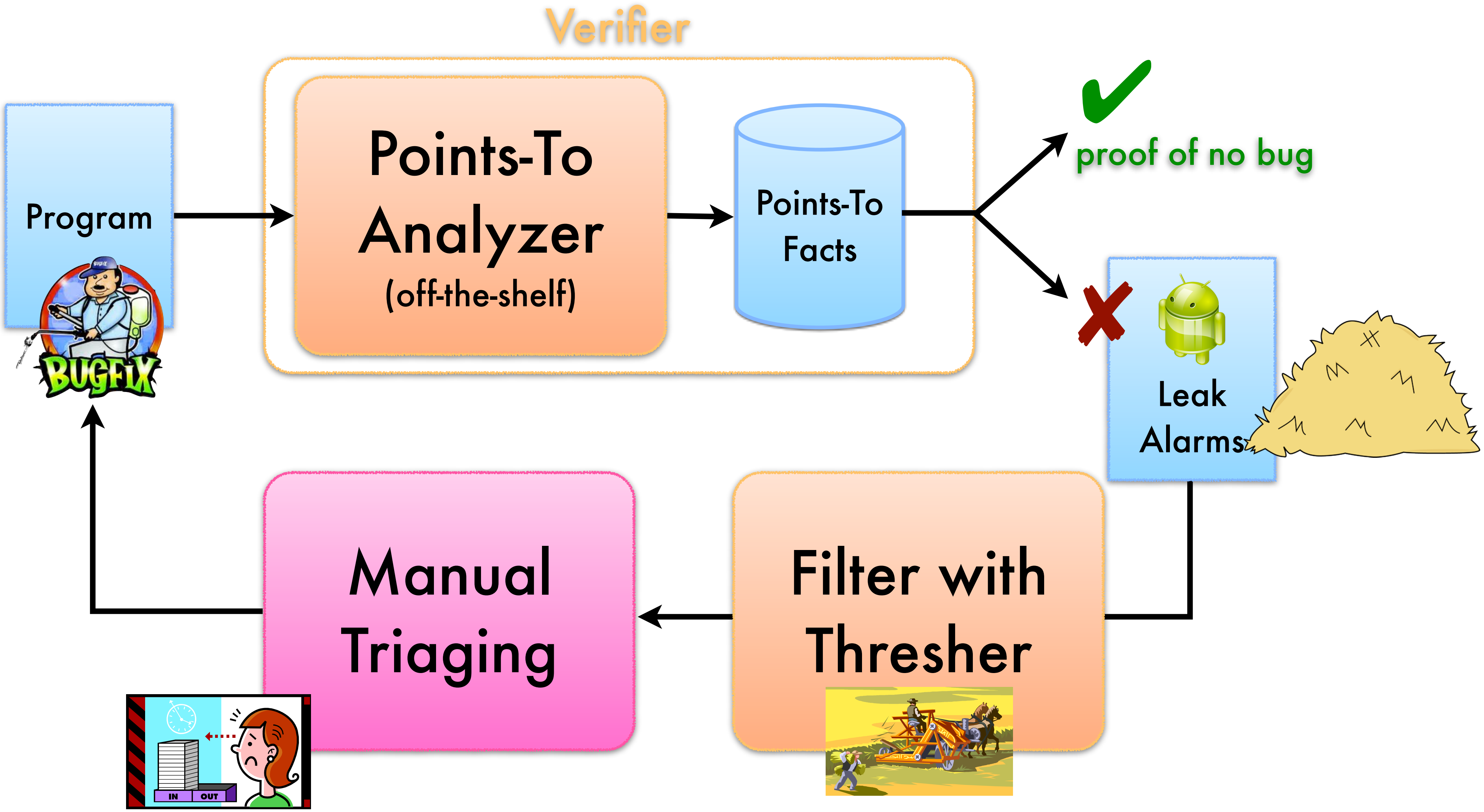

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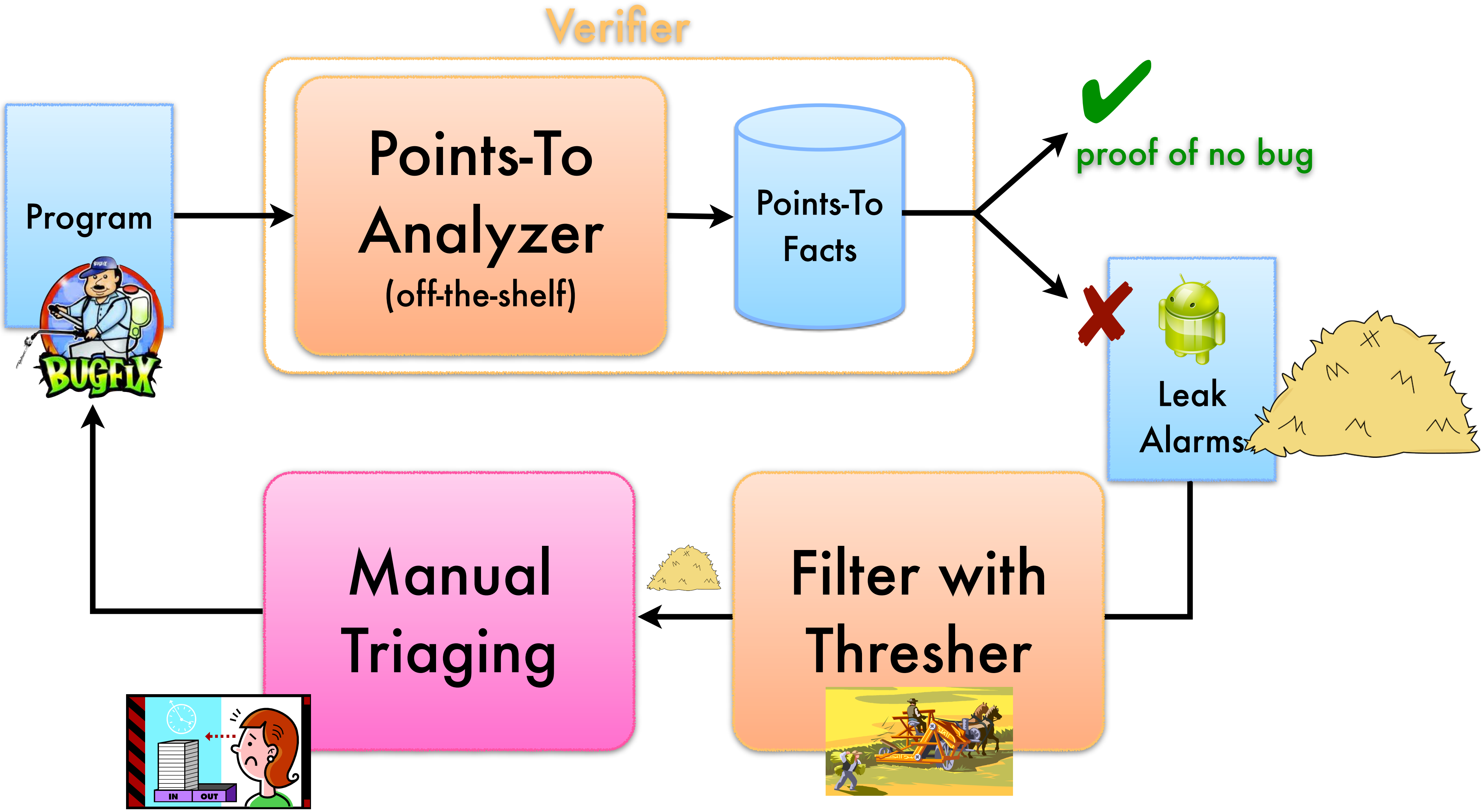

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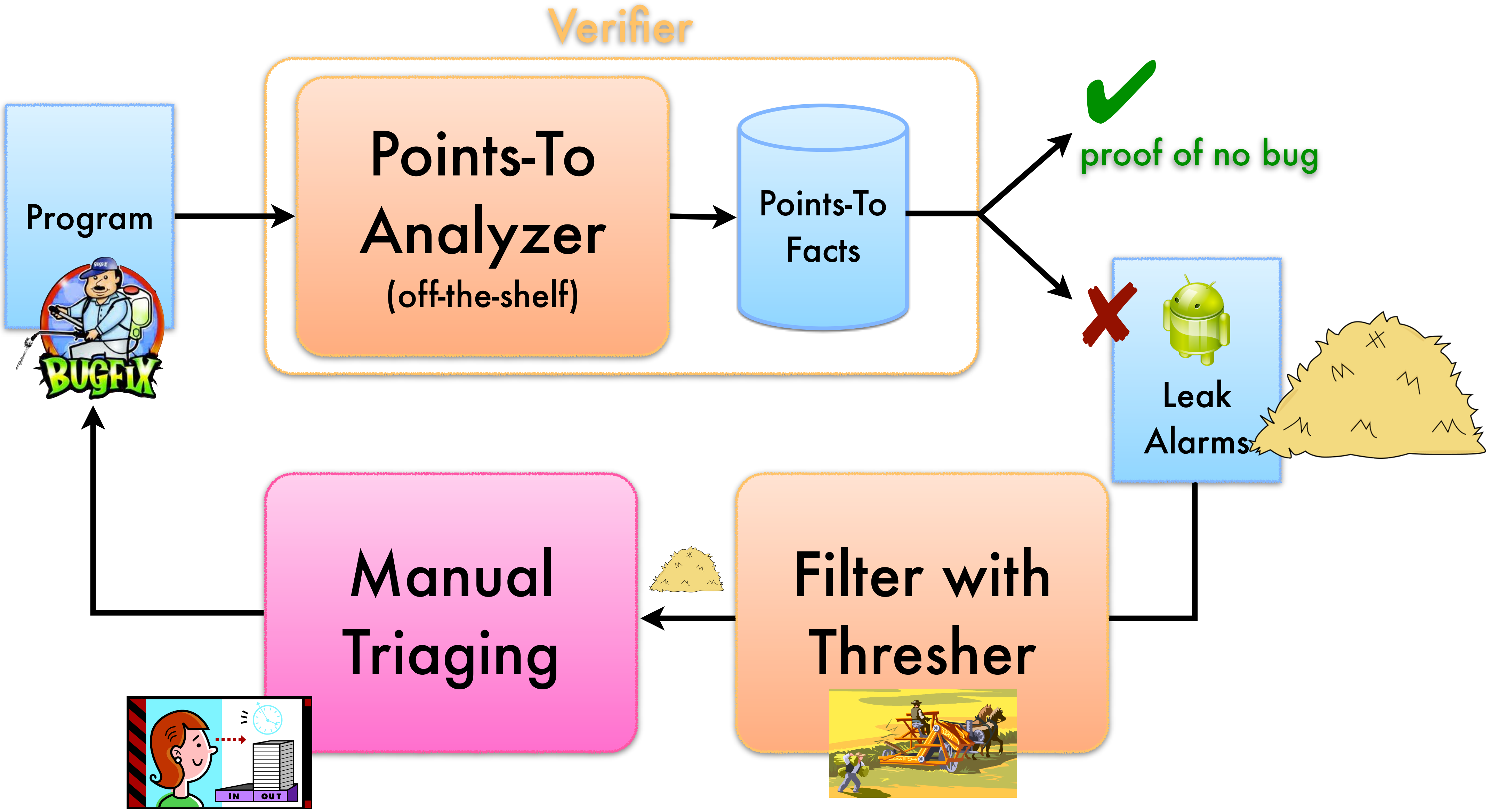

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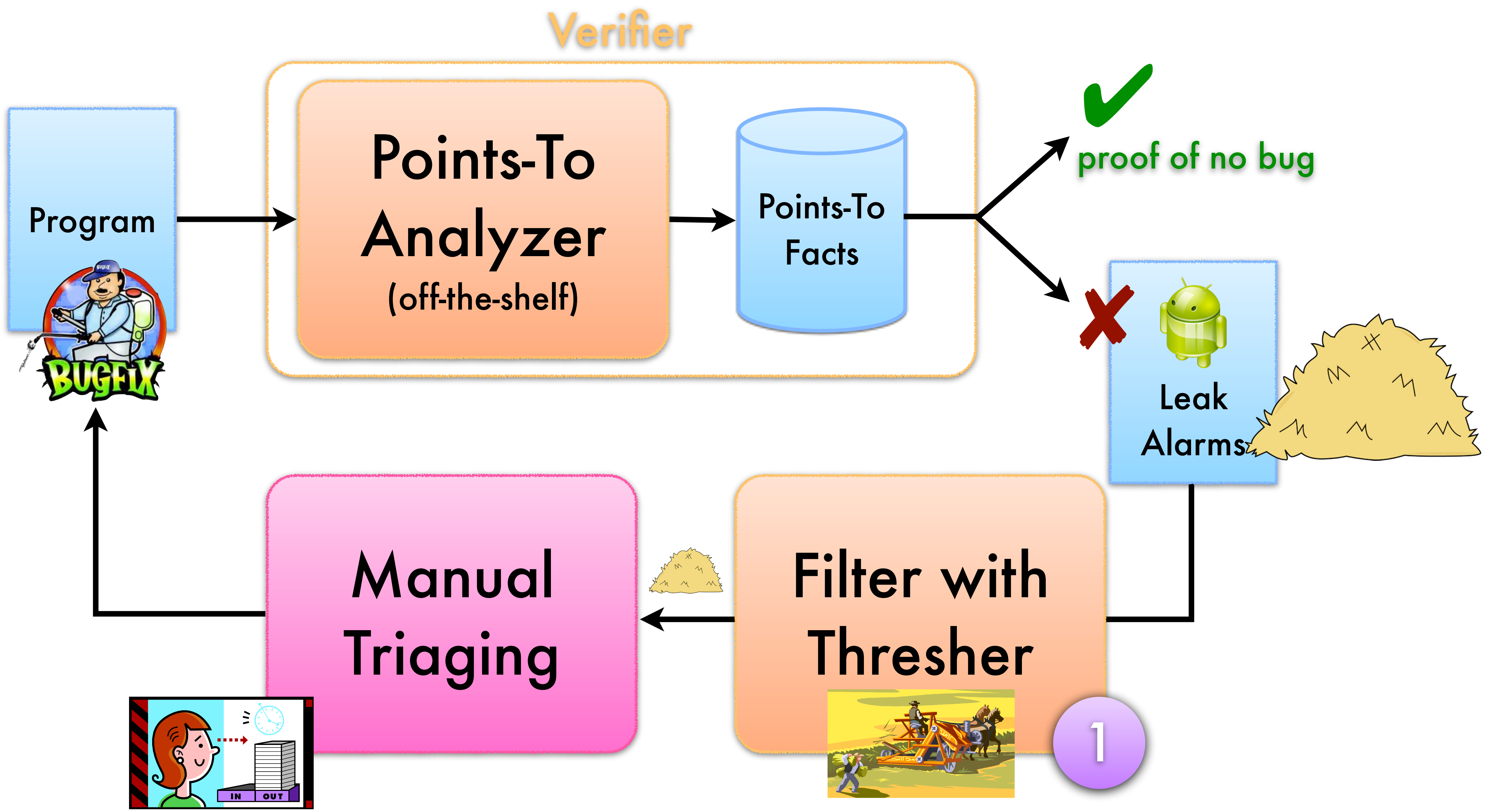


Idea 1: Refute points-to on-demand with second "uber-precise" filter analysis

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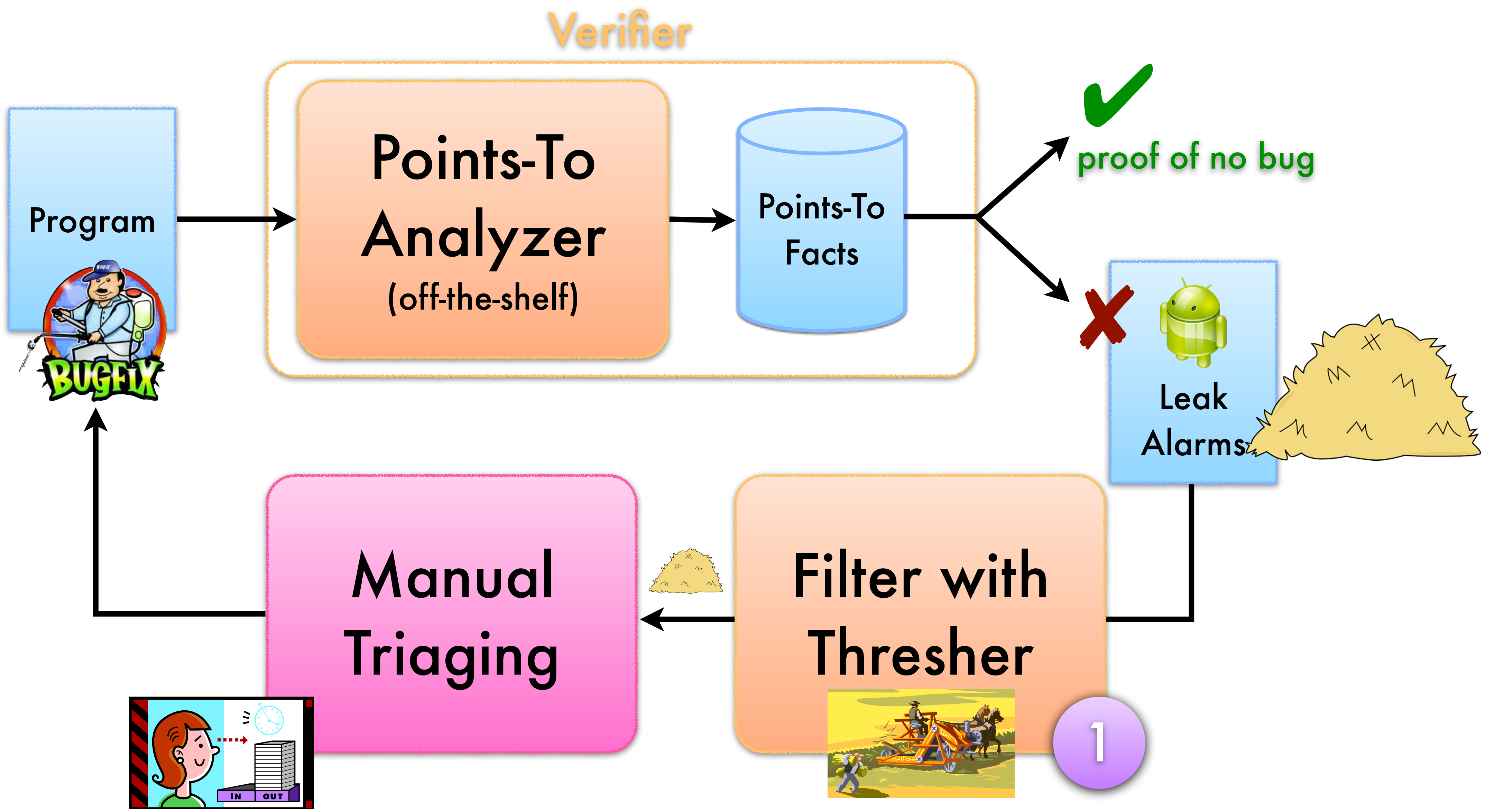


Idea (1): Refute points-to on-demand with second "uber-precise" filter analysis

*-sensitive

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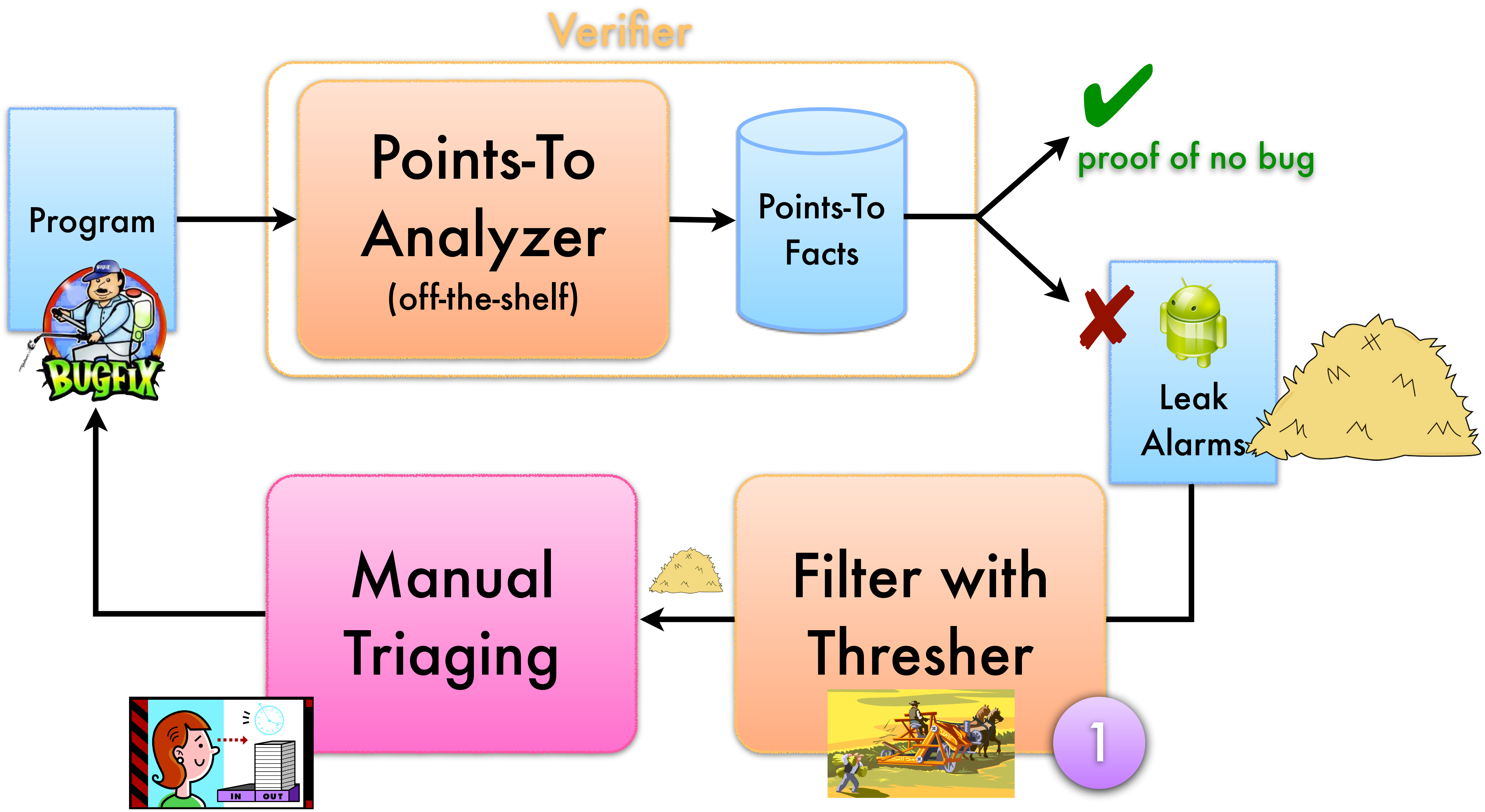


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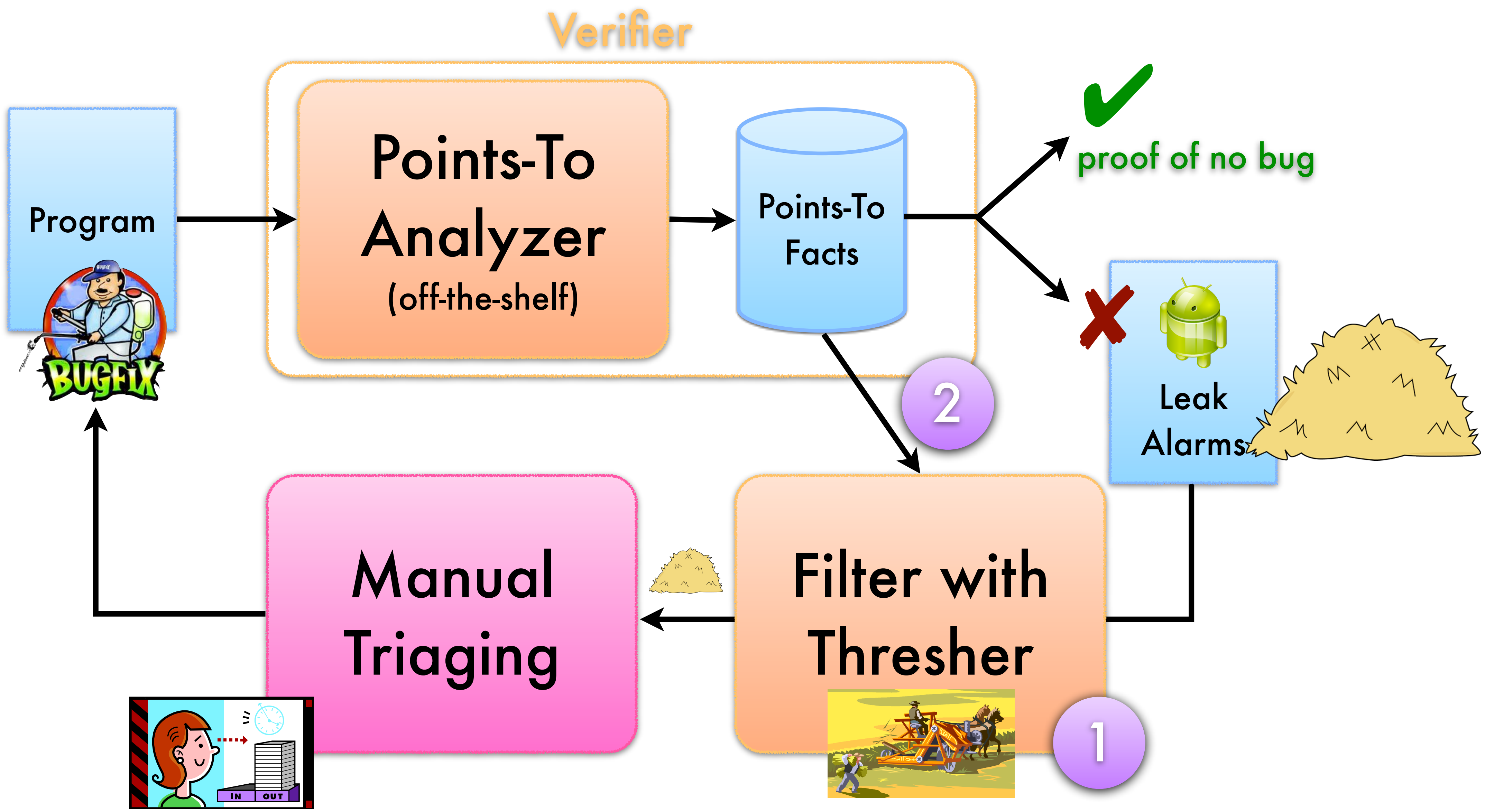


Idea 1: Refute points-to on-demand with second "uber-precise" filter analysis

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

# Refutation analysis is "Proof by Contradiction" with the "But Why?" game

1

# Refutation analysis is “Proof by Contradiction” with the “But Why?” game

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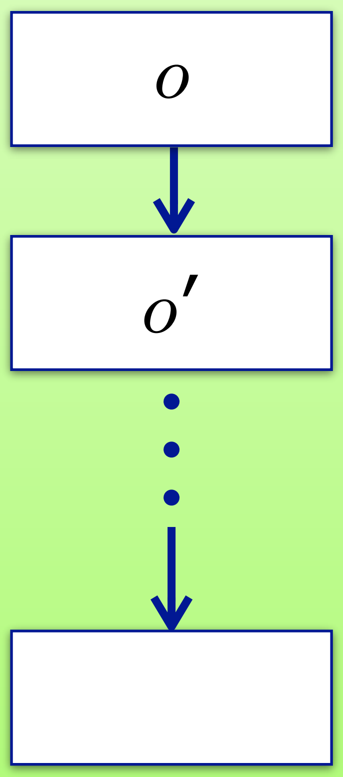
There **may** be an execution where at some time




of type T .

# Refutation analysis is “Proof by Contradiction” with the “But Why?” game



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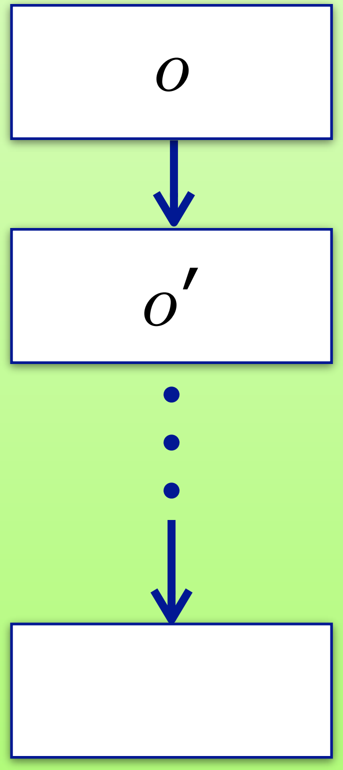


of type T .

A. Why does object $o$ possibly point to $o'$ ?

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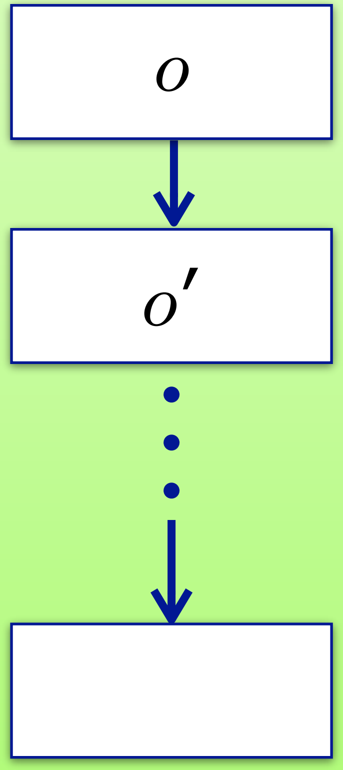


of type T .

A. Why does object $o$ possibly point to $o'$ ?

B. Because statement $s$ may execute to make $o$ point to $o'$

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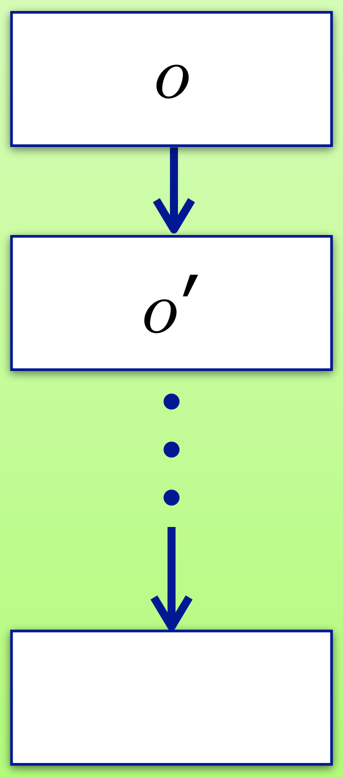


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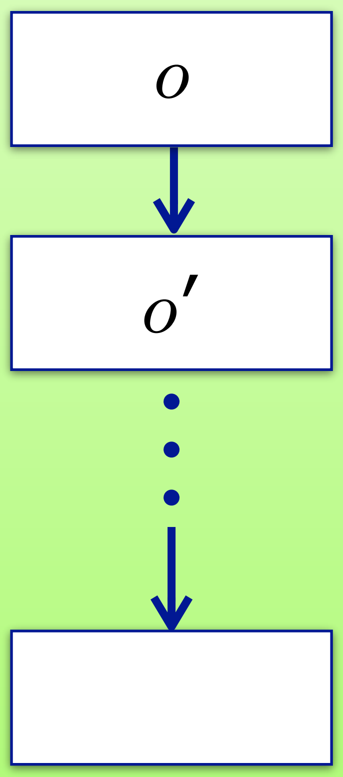


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B. Because before statement $s$, the program state could satisfy formula $\varphi$

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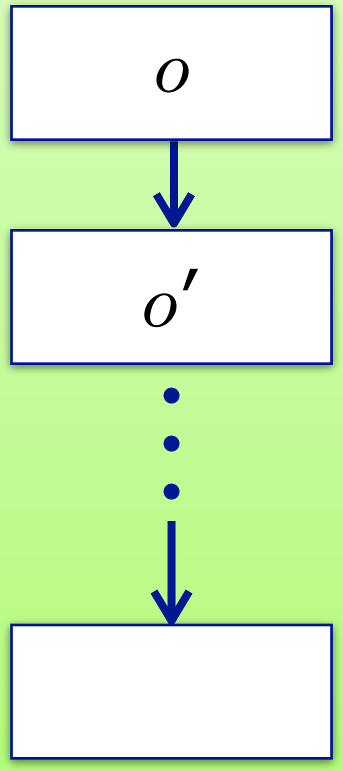


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A. Why does statement $s$ cause $o$ to point to $o'$ ?

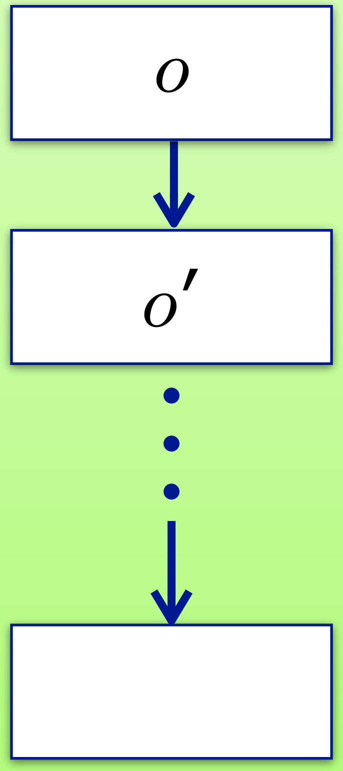
B. Because before statement $s$, the program state could satisfy formula $\varphi$

A. Why can the state before statement $s$ satisfy $\varphi$?

# Refutation analysis is "Proof by Contradiction" with the "But Why?" game



There **may** be an execution where at some time




of type T .

A. Why does object $o$ possibly point to $o'$ ?

B. Because statement $s$ may execute to make $o$ point to $o'$

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B. Because before statement $s$, the program state could satisfy formula $\varphi$

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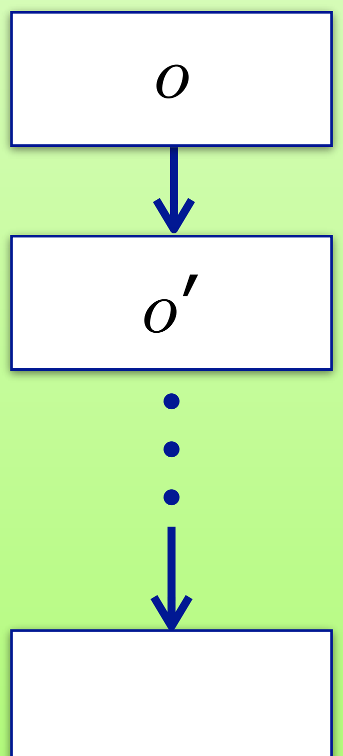


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A just asks "but why?"

B reasons about program semantics

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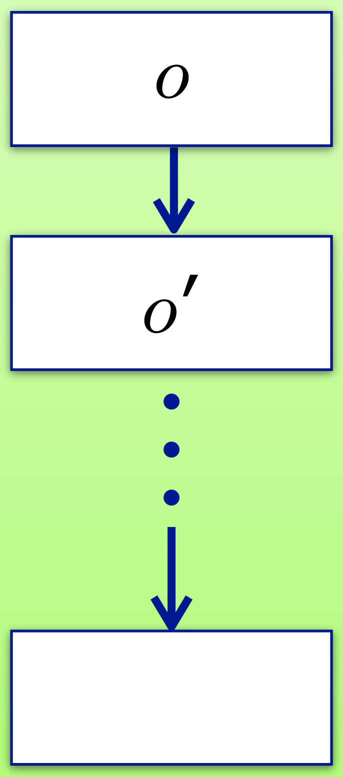


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Theorem: If B can't give an answer, contradiction. The alarm is false. It's been refuted. (A wins)

# Leverage first analysis by designing specialized constraint forms

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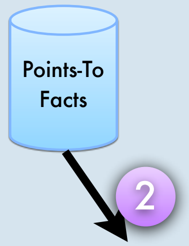
# Leverage first analysis by designing **specialized** constraint forms

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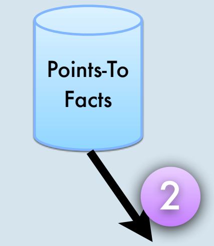


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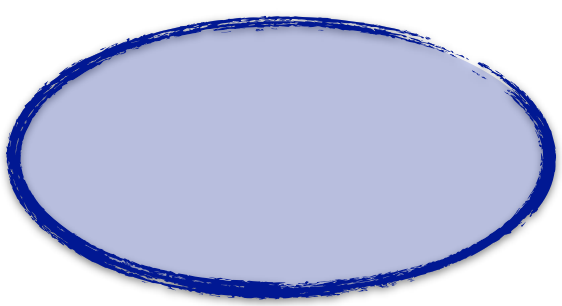

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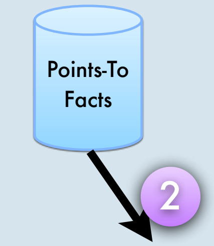


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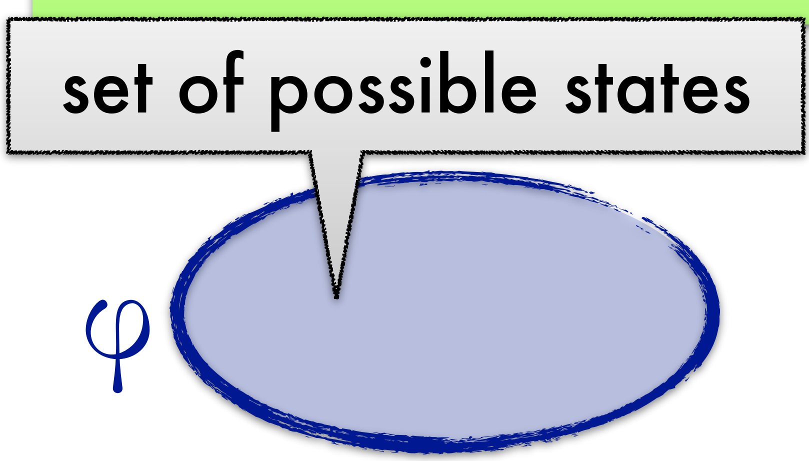

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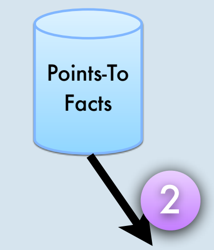


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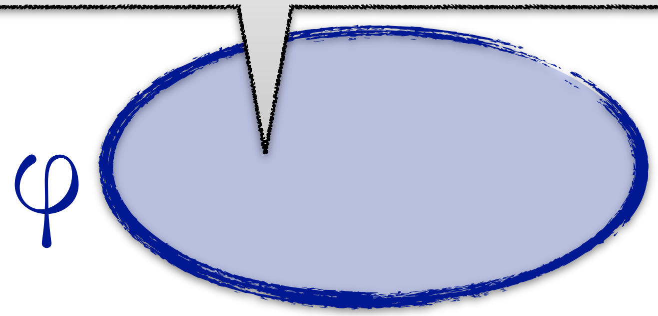
if empty, then refuted (A wins)

set of possible states



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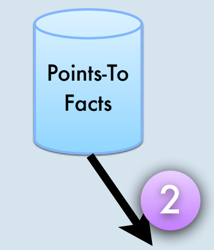


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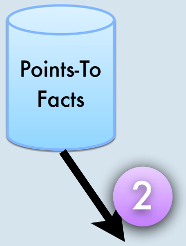


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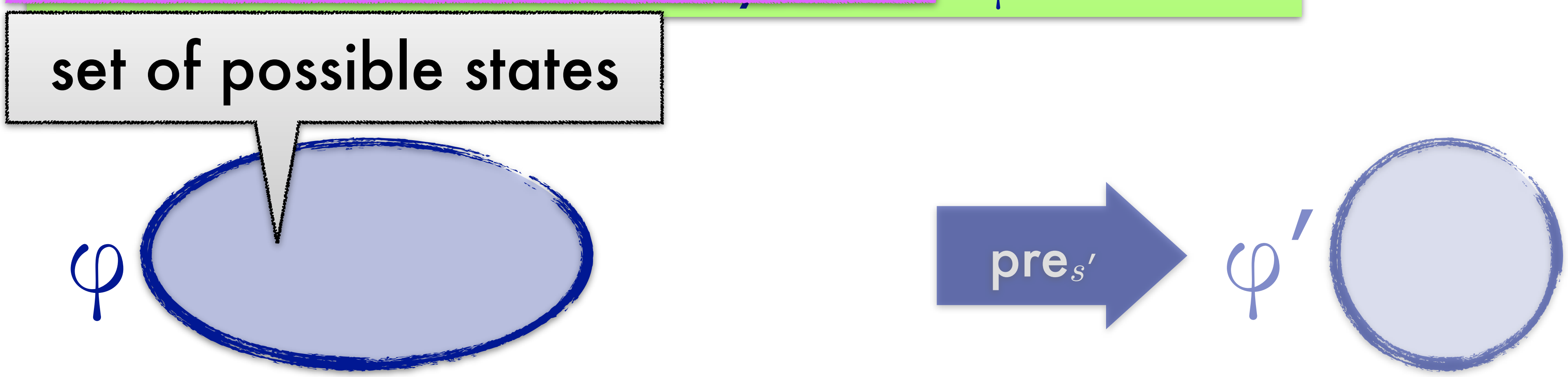

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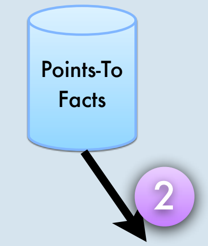


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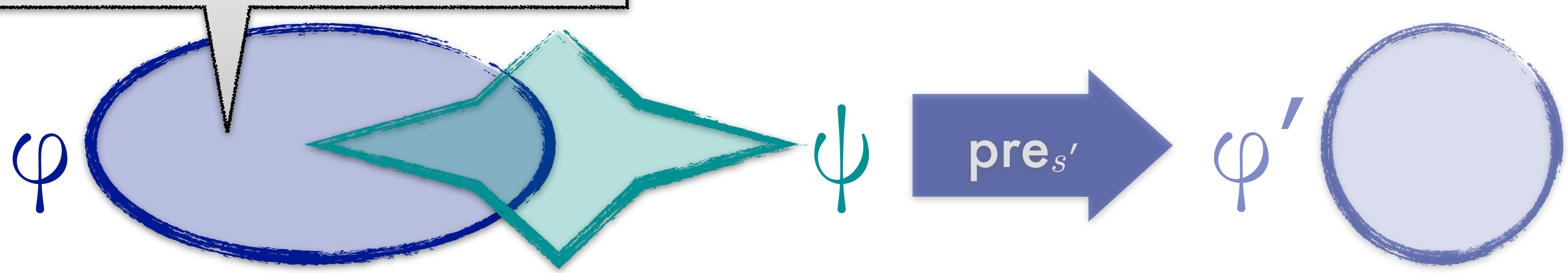

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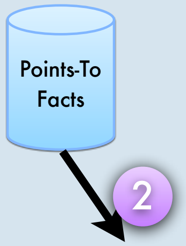


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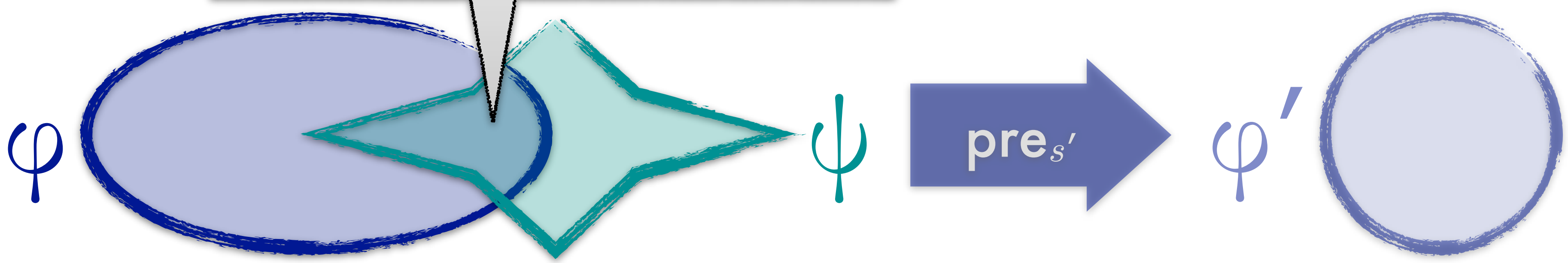

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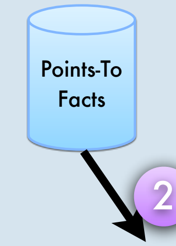


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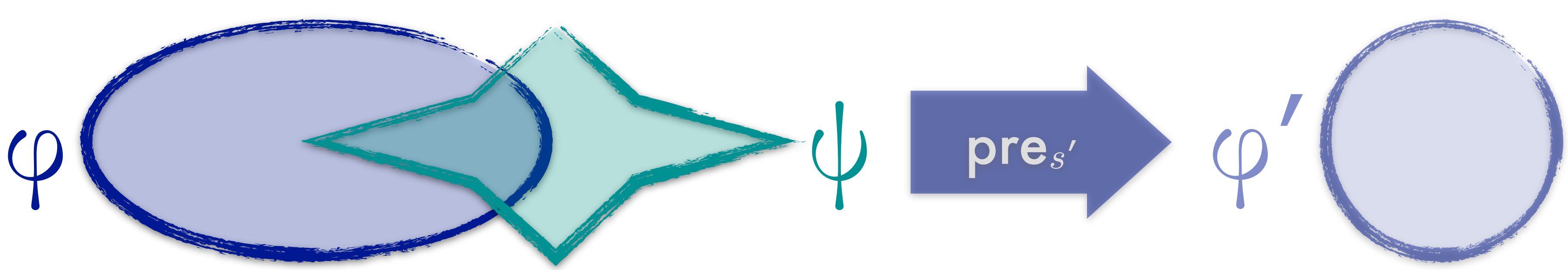

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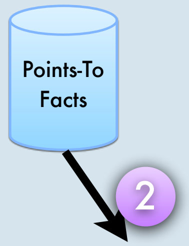


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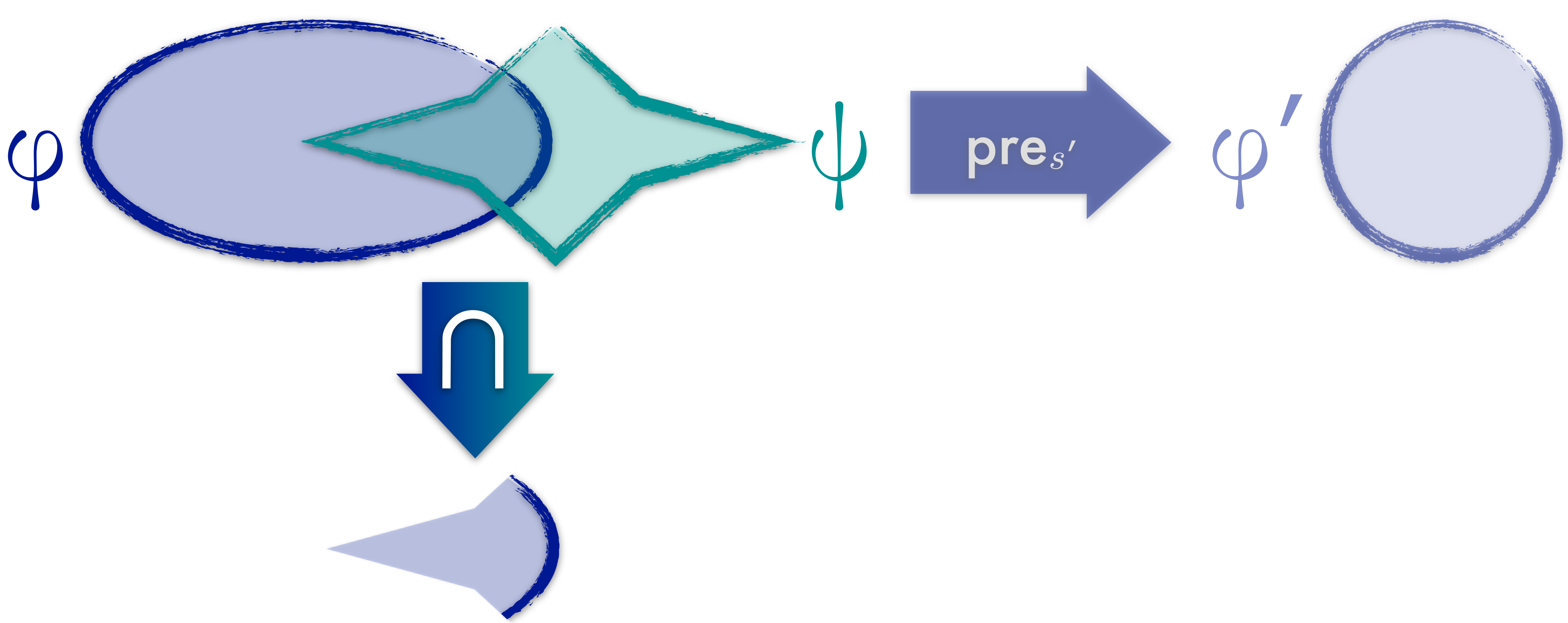

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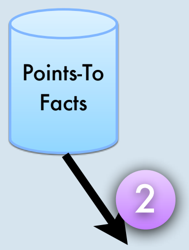


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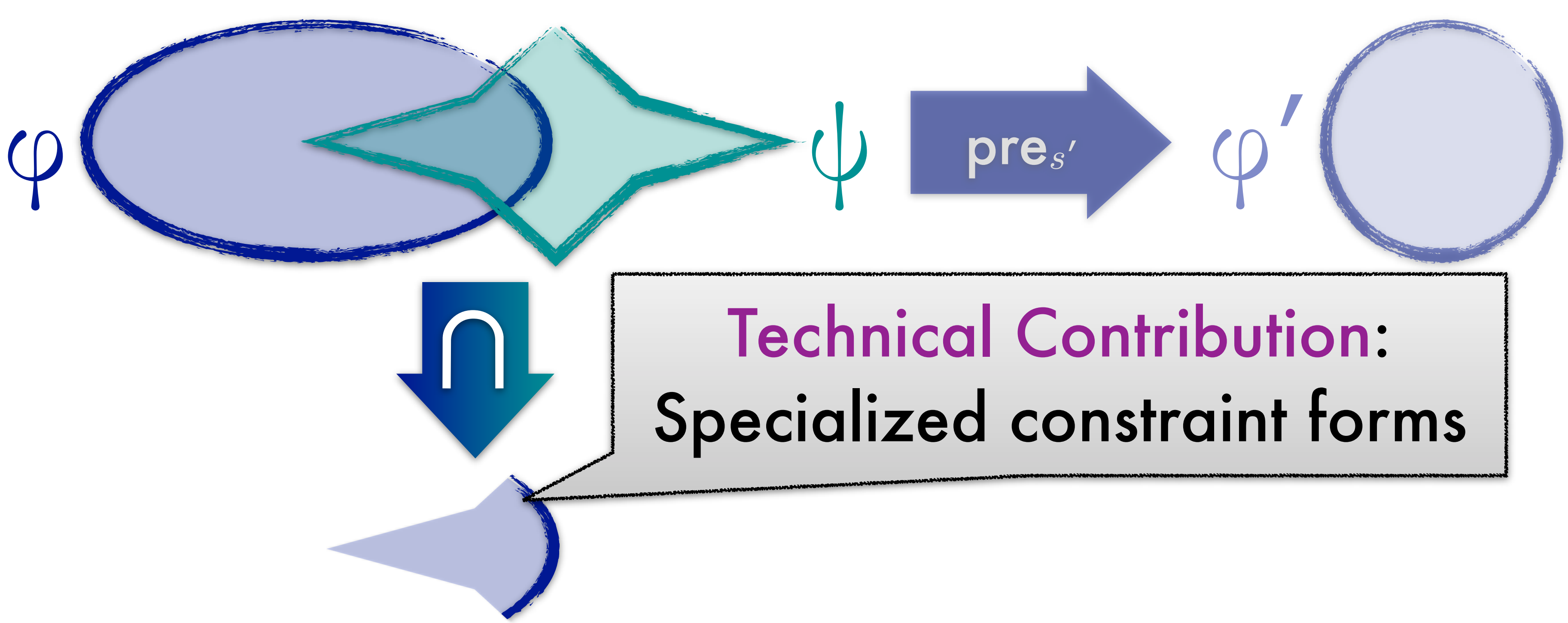

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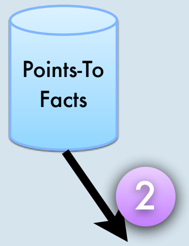


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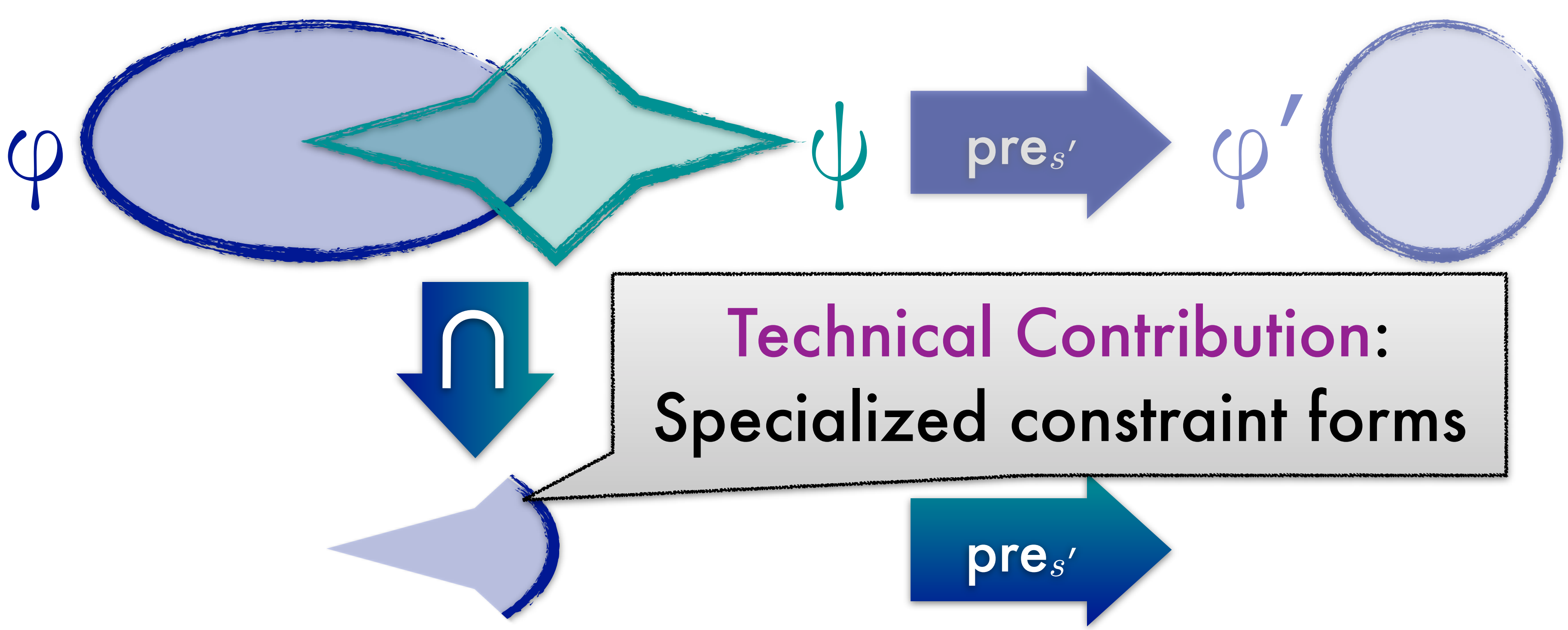

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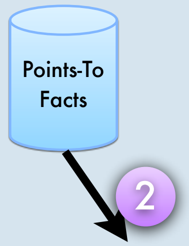


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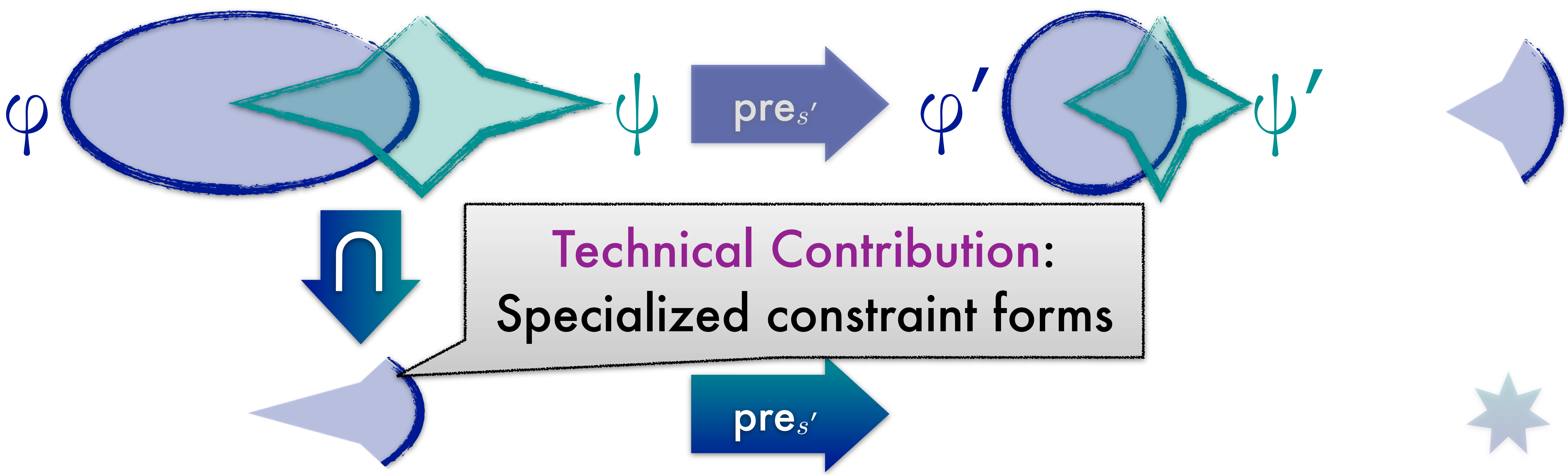

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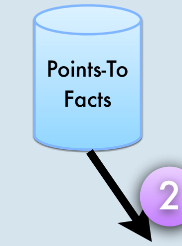


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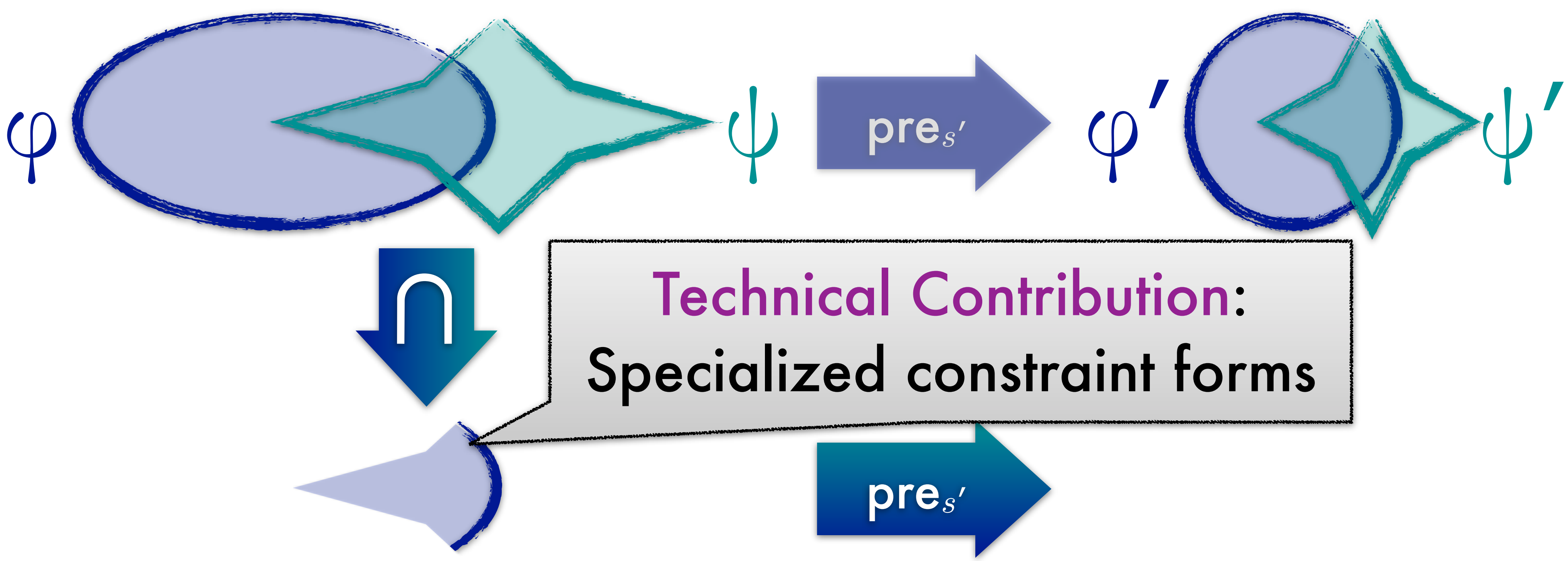


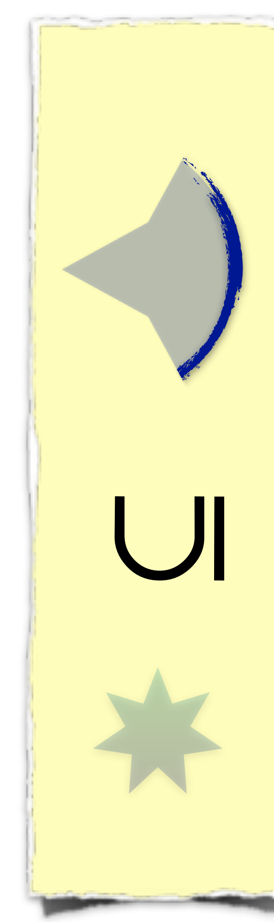

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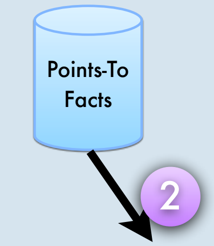


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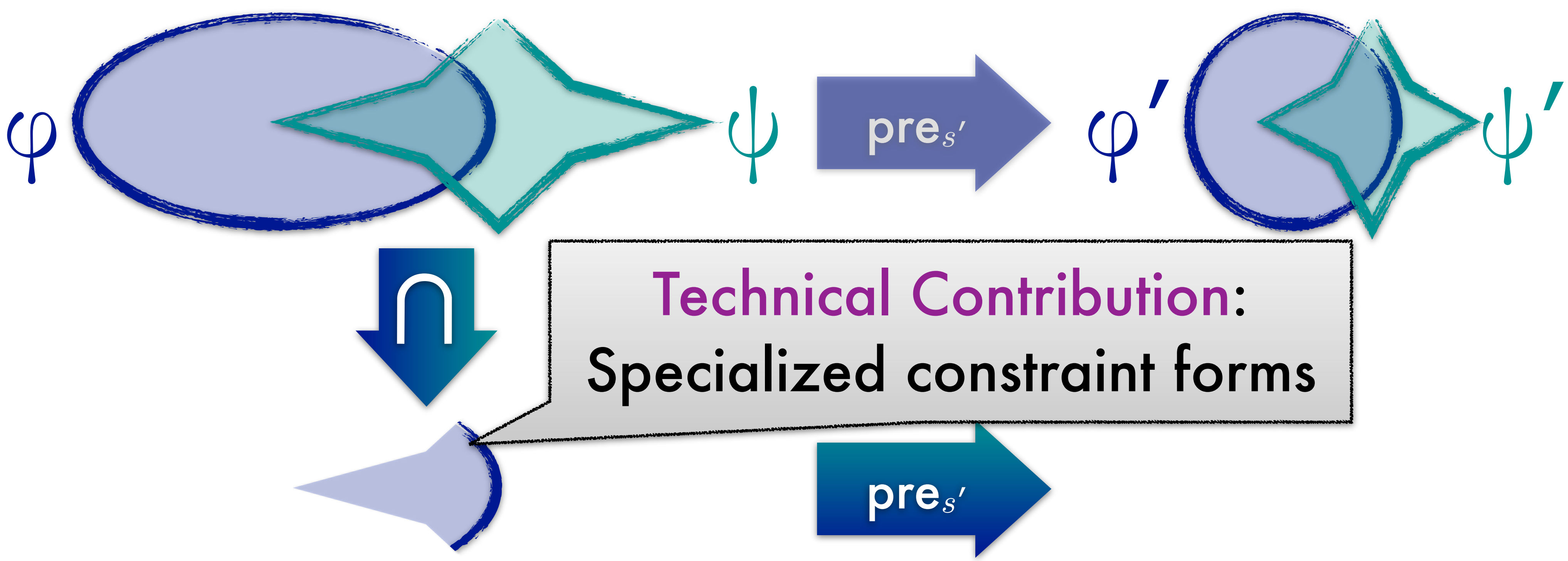
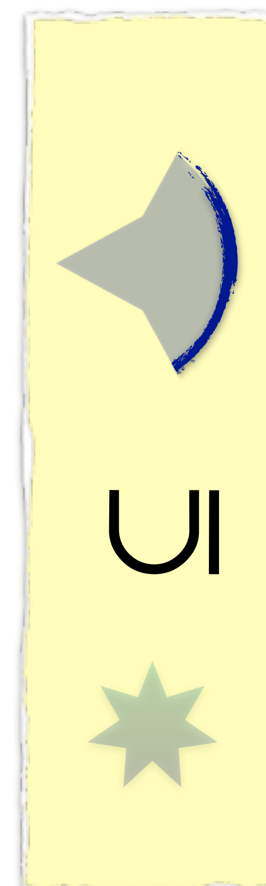
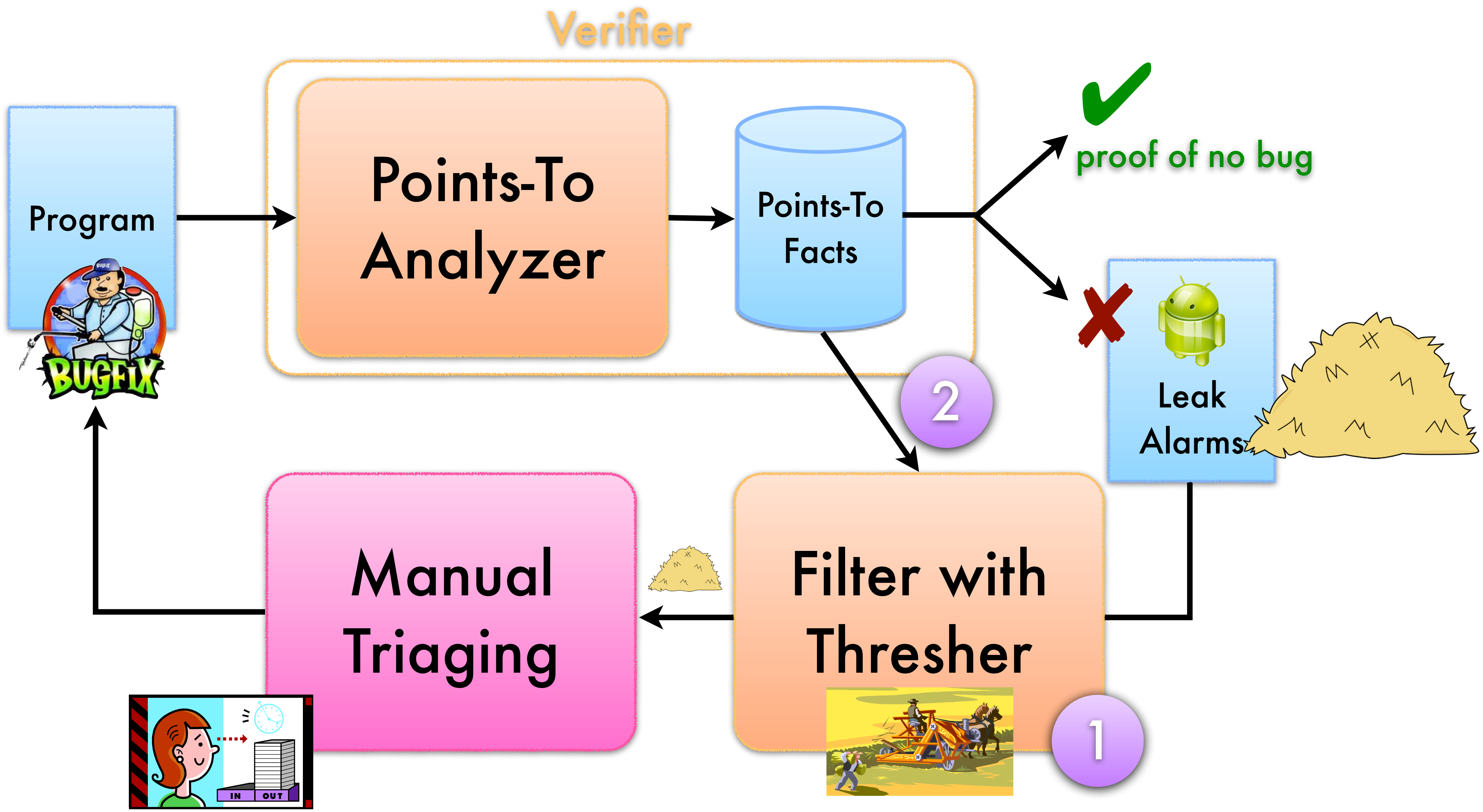
**Specialized constraint forms makes finding refutations feasible**



# Summary: Thresher assists the user with alarm triaging by effectively filtering out many false alarms.




Idea 1: Refute points-to on-demand with second "uber-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

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| 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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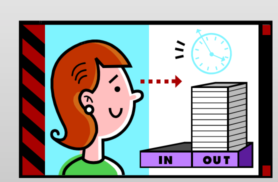
`staticfield-Activity` pairs

Filtered

Manual



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`staticfield`-`Activity` pairs

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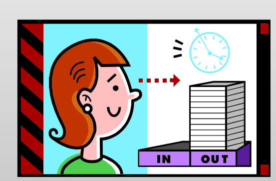

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< ~coffee to lunch break

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% after filtering

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| **Total** | **72K** | **311** | **172** | **115** | **1602** | **17** | **88** |

% after filtering

# Is Thresher effective at filtering?

| 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 |
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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

Guesstimate

Triage "well" without versus with: ~450 hours versus ~30 hours

Triage "ok" without: ~30 hours

| | | Alarms | Refuted | Bugs | Time (s) | Alarm % | ed % |
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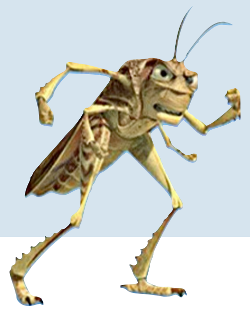
Android
OS


... in the process of finding leaks in apps

# Find the Android's HashMap bug ...



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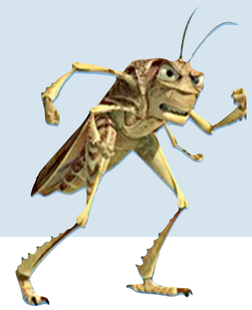

null object pattern: should not be written to

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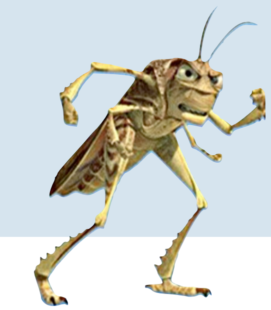

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An "evil" implementation of the `Map` interface can corrupt `EMPTY`. Then, all `HashMaps` created in the future will be corrupted.

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return 0

return "evil" content

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  s
  H

  v

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What if you store **passwords** in a `HashMap`?

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# Find the Android's HashMap bug ...

```
cla
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```

**What if you store passwords in a `HashMap`?**

**We reported this, Google fixed it**

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

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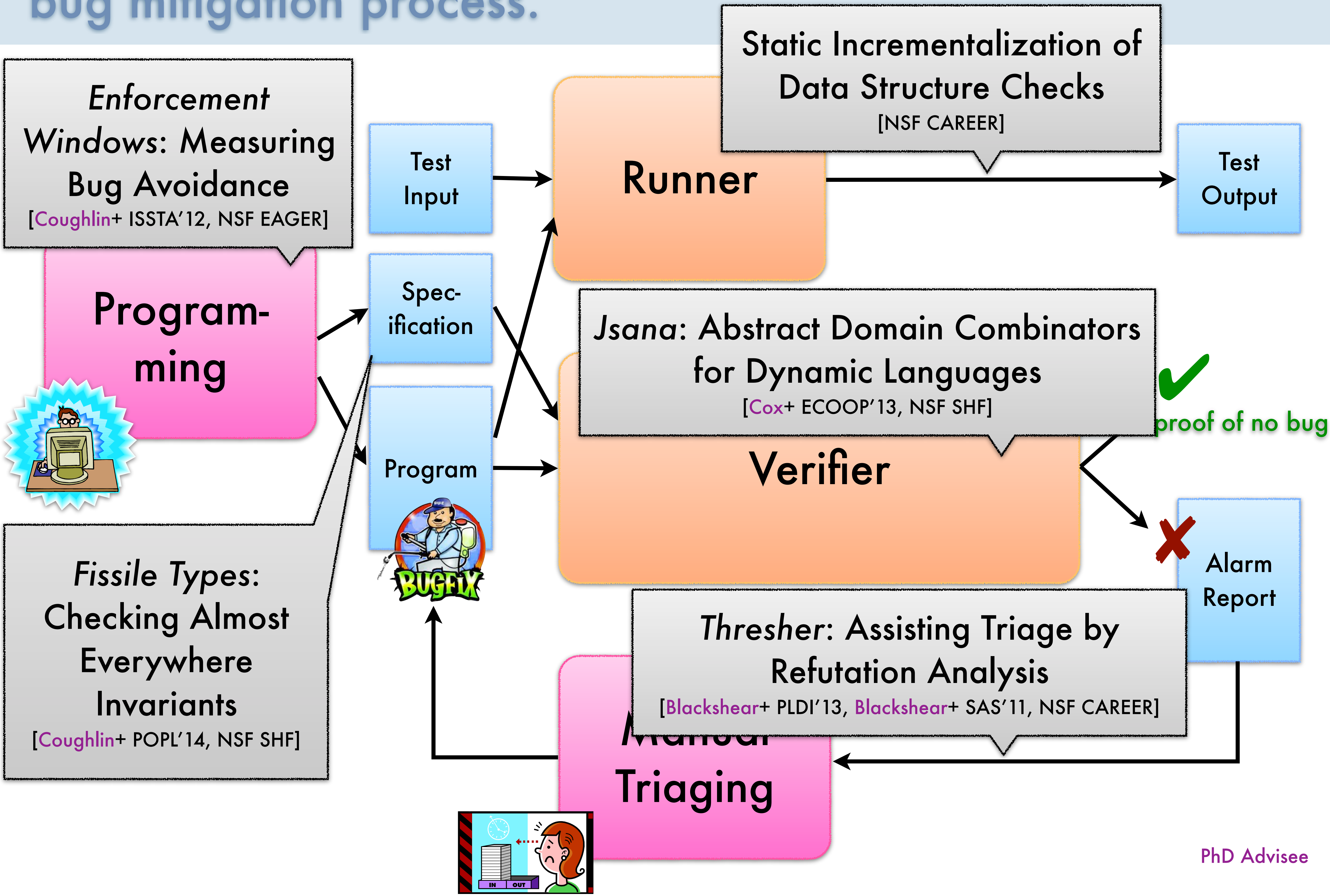
An "evil" implementation of the `Map` interface can corrupt `EMPTY`. Then, all `HashMap`s created in the future will be corrupted.

Contribution: Addressed the false alarm problem with

a “smart and precise filter”

a refutation analysis

# Agenda: The cooperative approach addresses the whole bug mitigation process.



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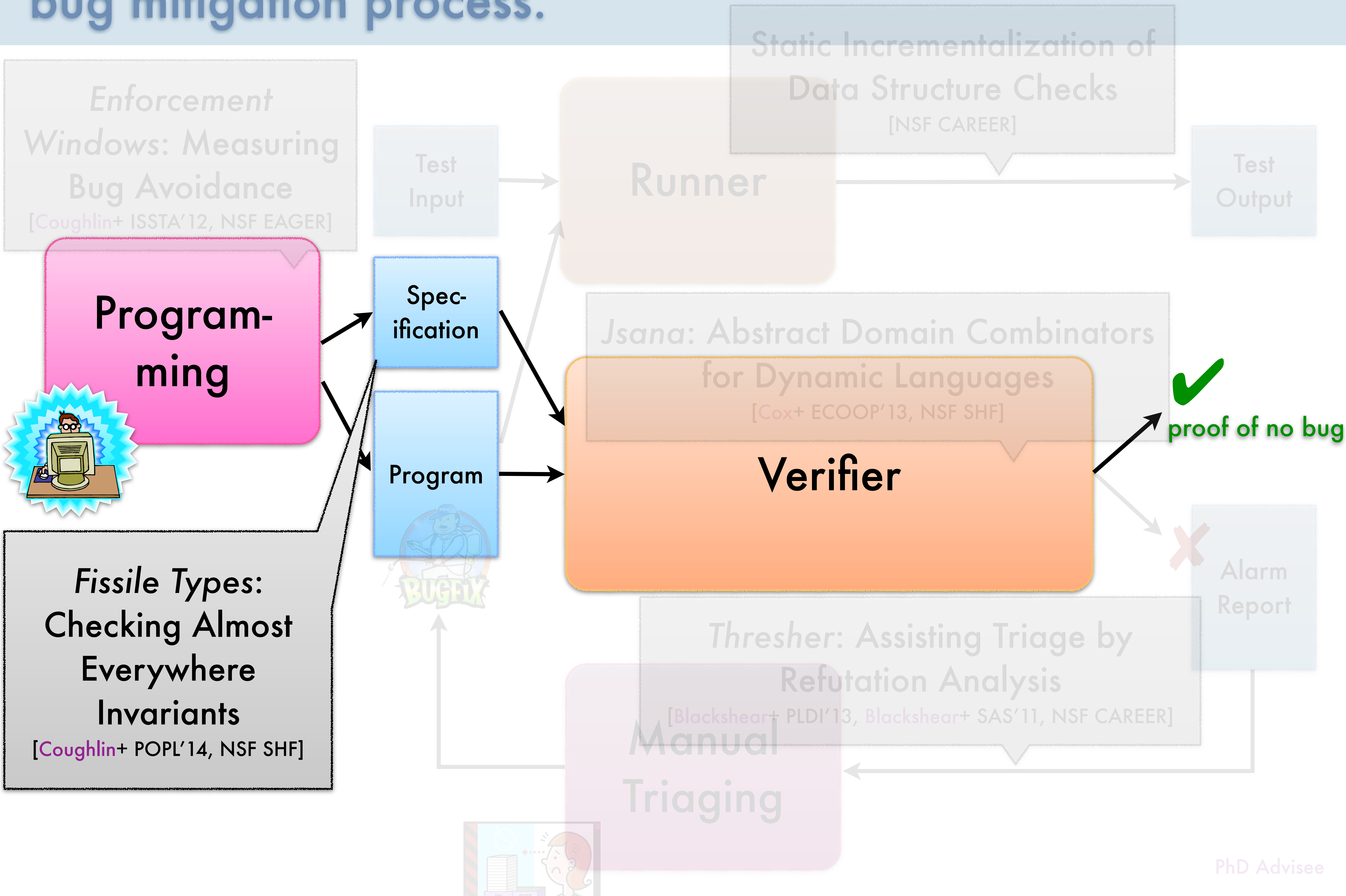

# Fissile Types: Checking Reflection with Almost Everywhere Invariants

# Method Reflection and the Great Divide

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```
object[string]()
```

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reflective method call: dispatch based on run-time value (in `string`)

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Type system designers **worry**.

What gets called? What if `object` has no method named by `string`?

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reflective method call: dispatch based on run-time value (in `string`)

`object[string]()`

**type system designers**

**"web 2.0" developers**

Type system designers **worry**.

What gets called? What if `object` has no method named by `string`?

"Web 2.0" developers think it's **cool**.

I can flexible and compact code, so I will take it over static safety.

# Method Reflection and the Great Divide

reflective method call: dispatch based on run-time value (in `string`)

```
object[string]()
```

**type system designers**

**"web 2.0" developers**

Type system designers **worry**.

Wh

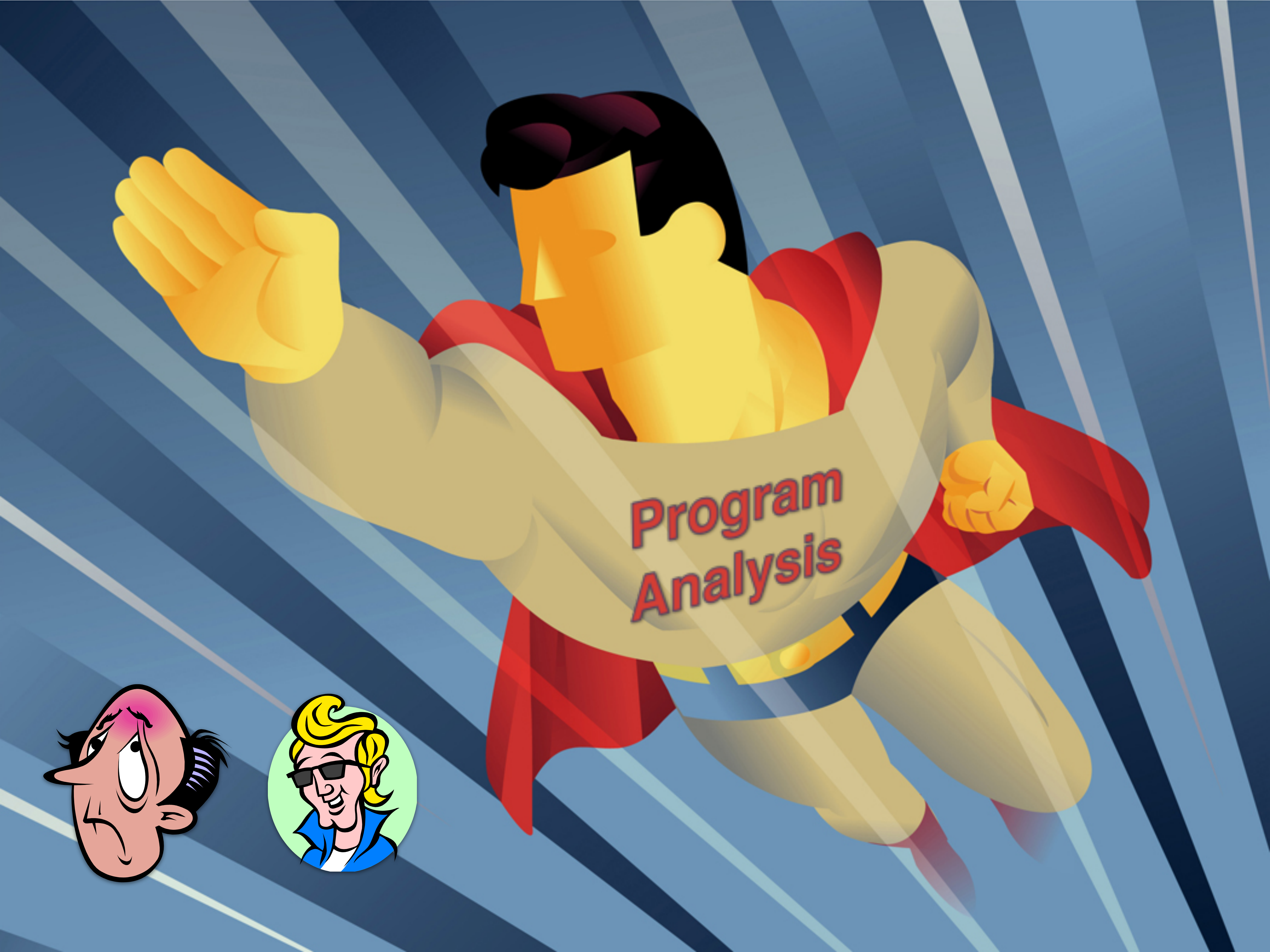
obj

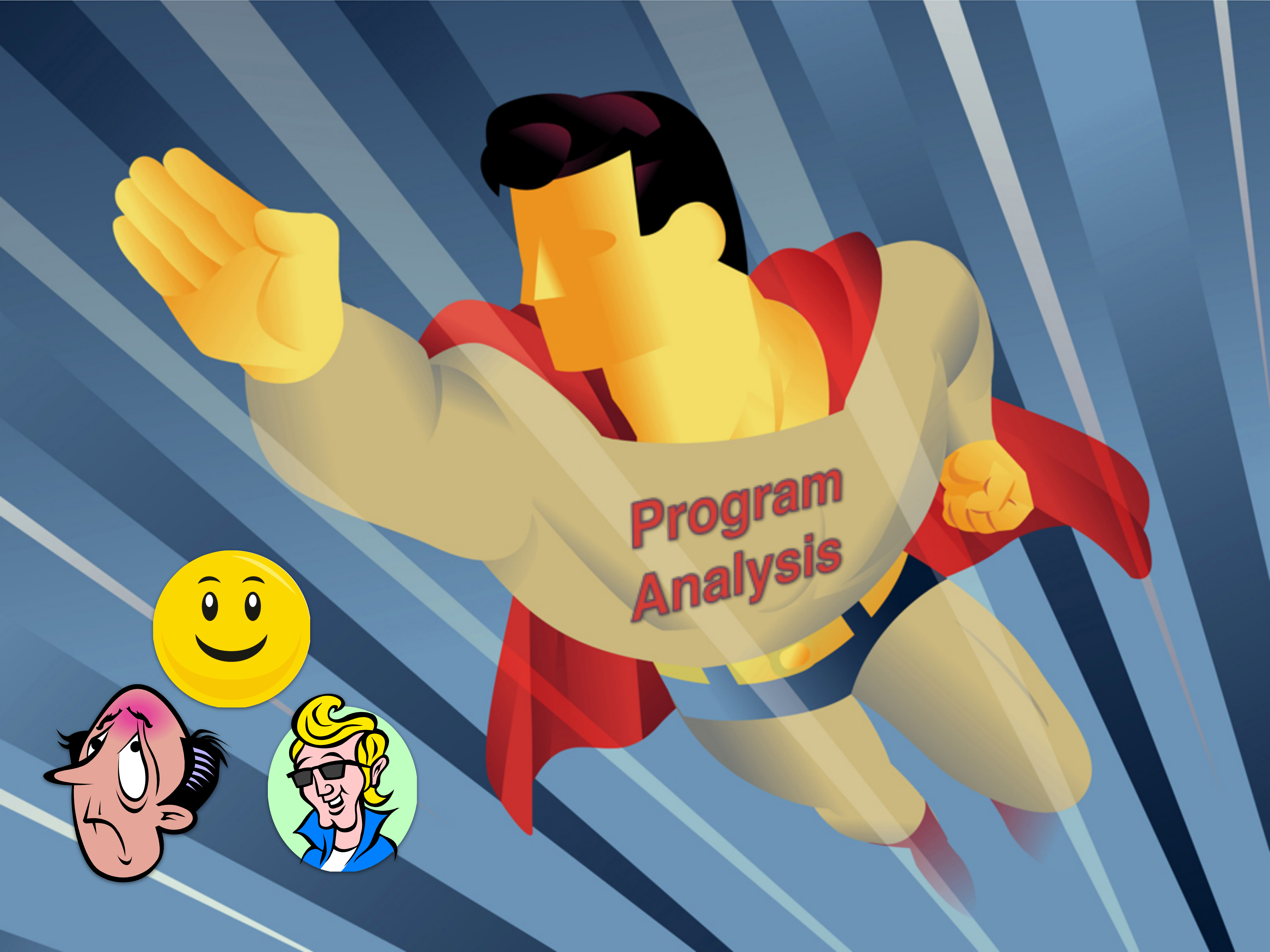
by

"Web 2.0" developers think it's **cool**.

static safety.

"MethodNotFound" checked at run time


Program
Analysis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# (1) safe, (2) not type safe, (3) but almost so

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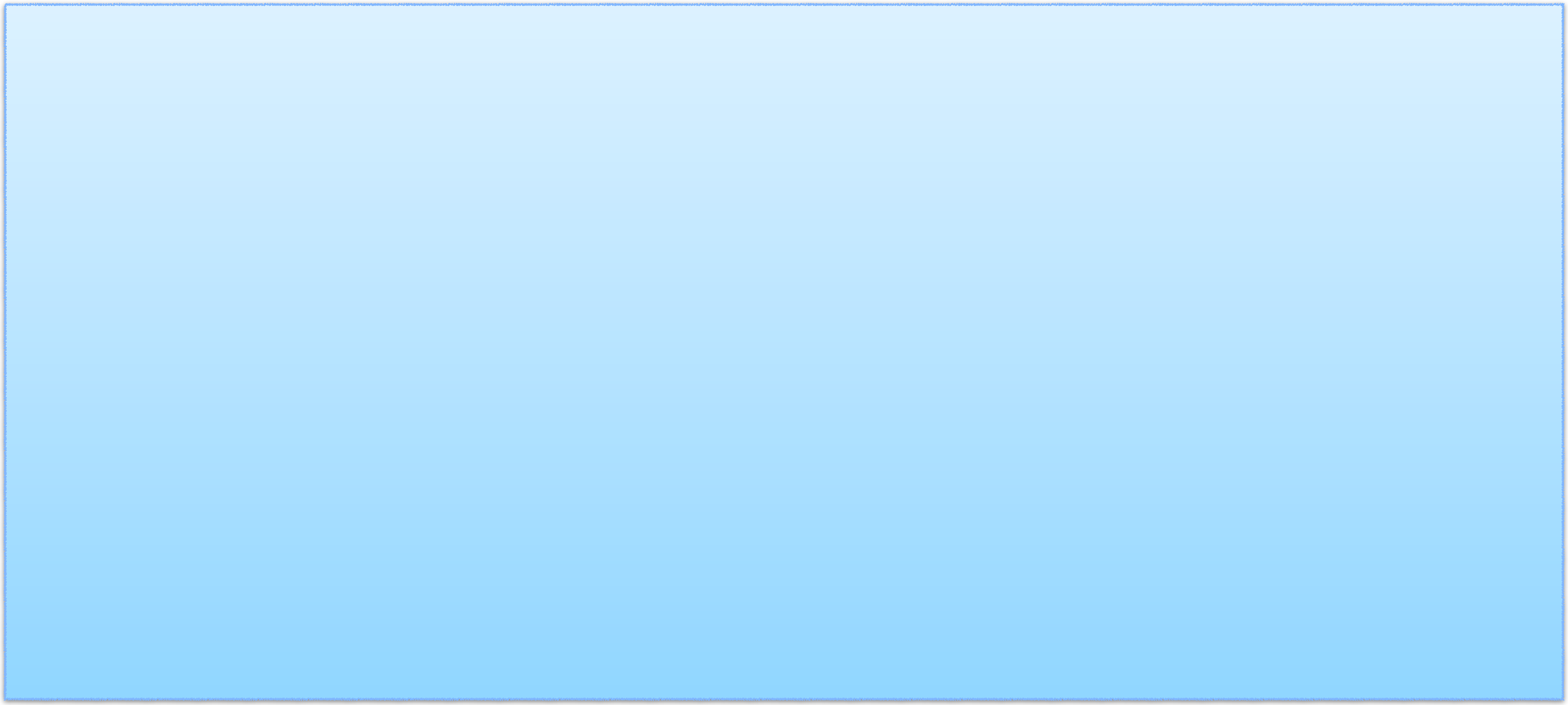

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safe assuming a relationship invariant between `.o` and `.m`

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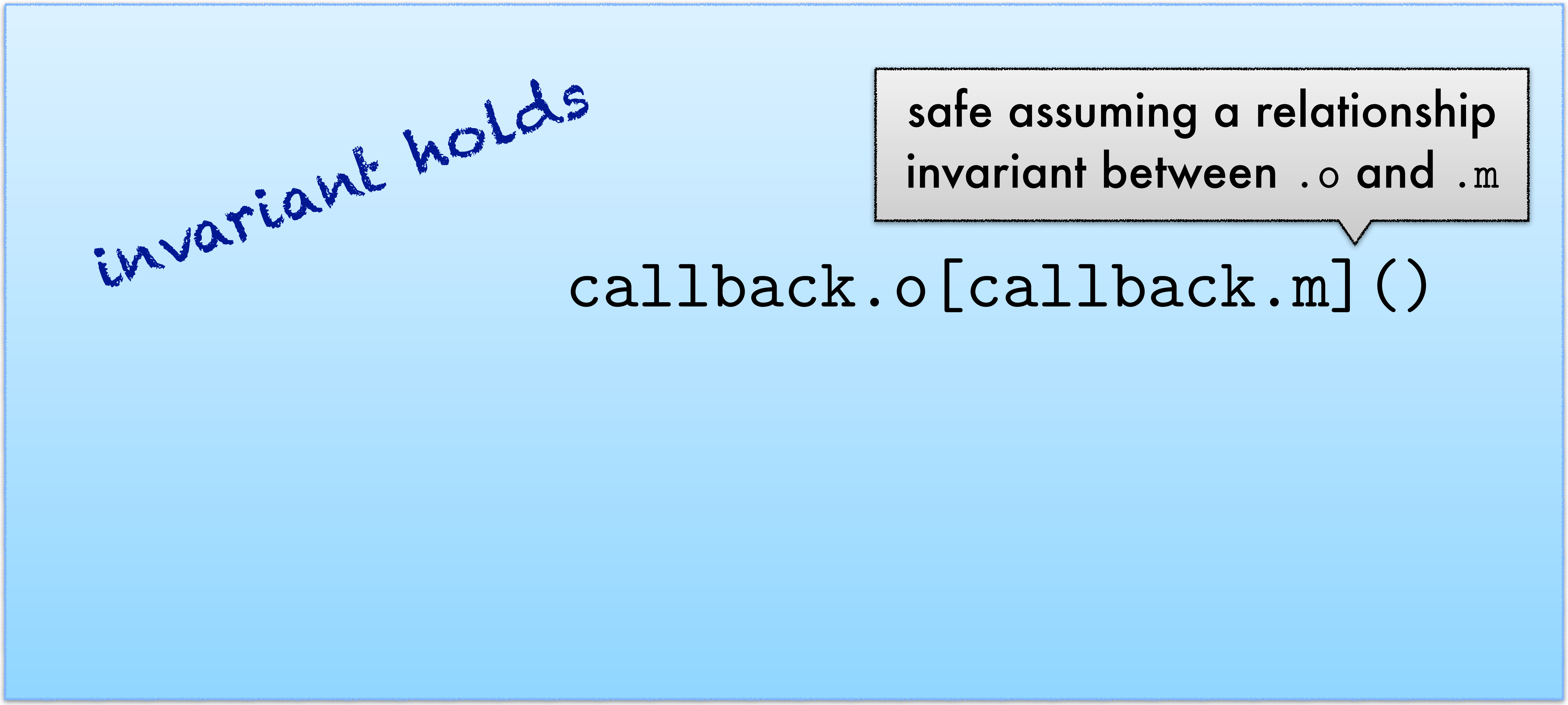


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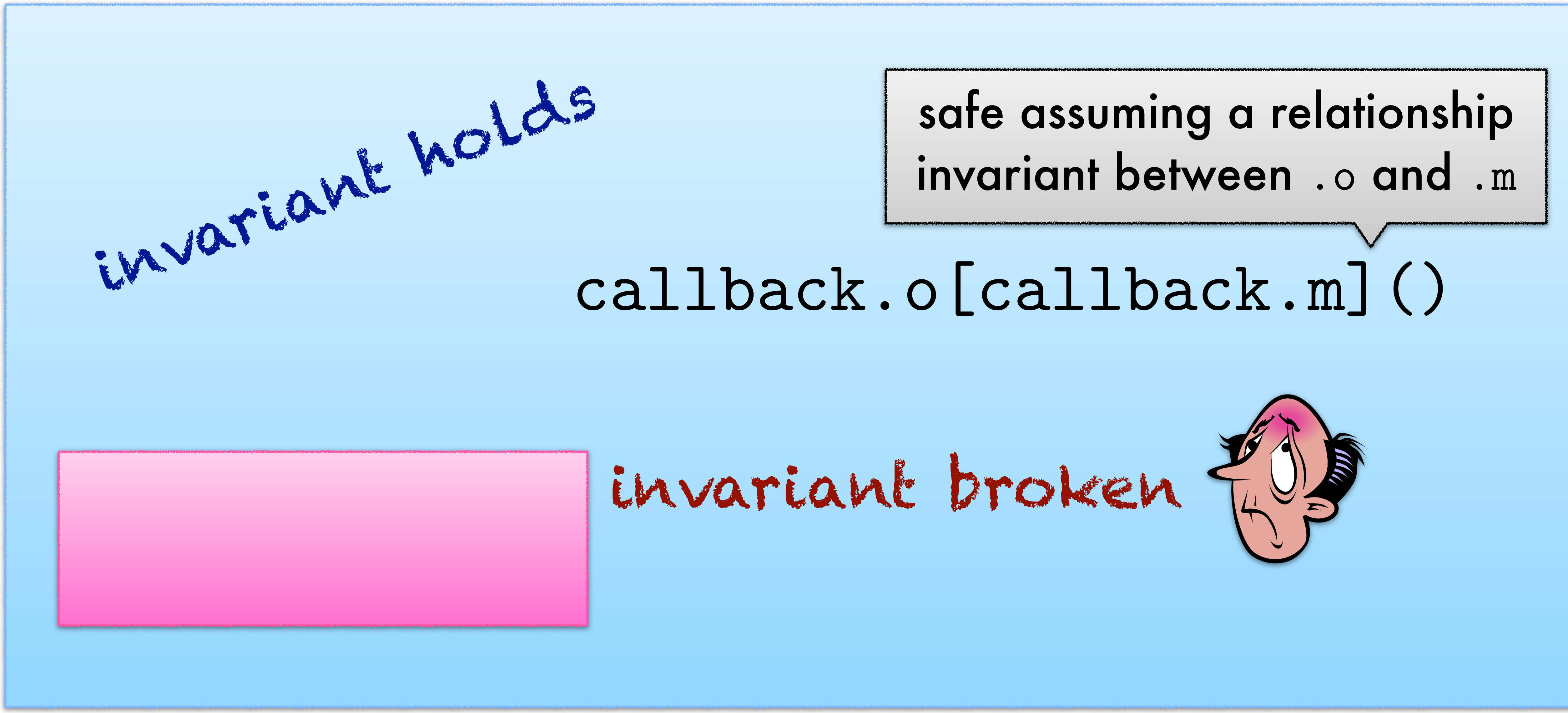


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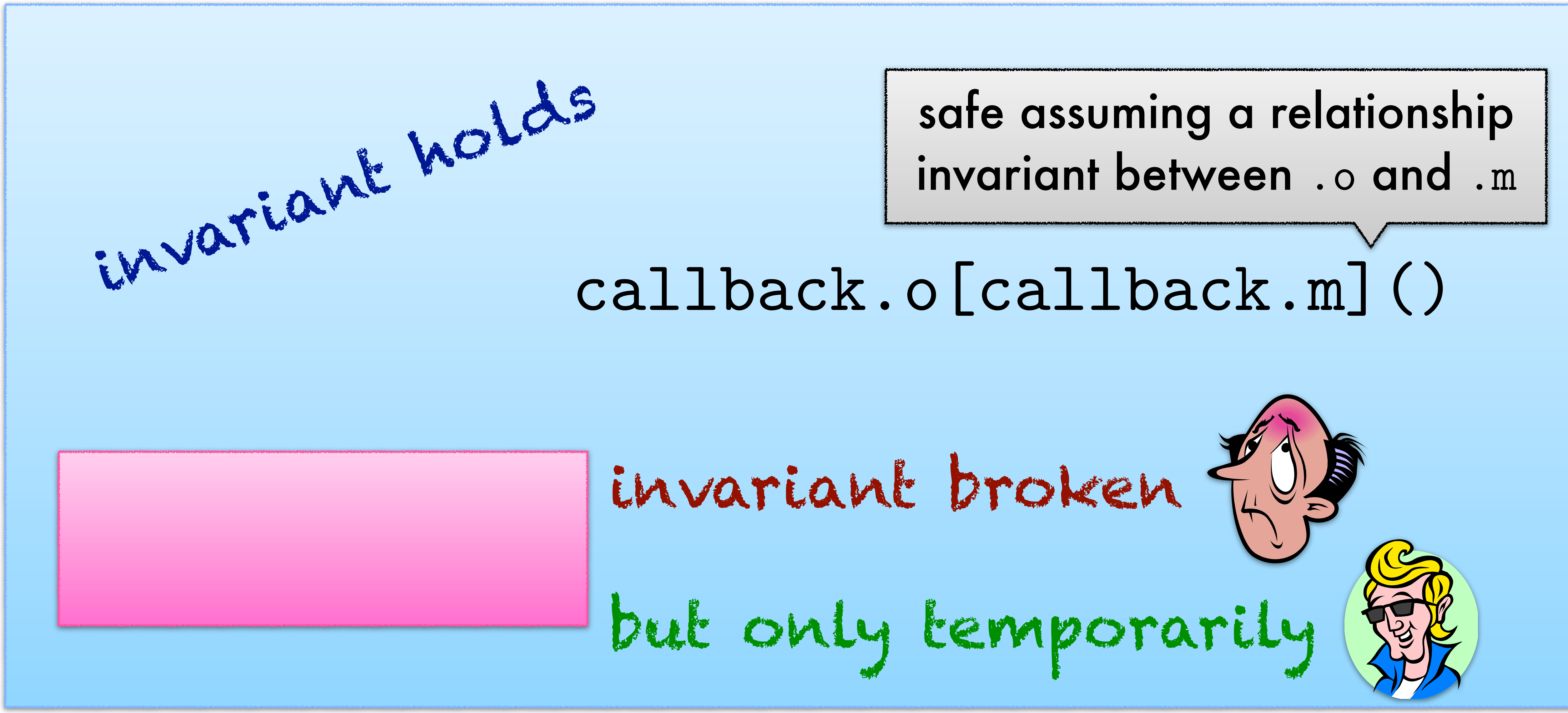


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invariant holds

safe assuming a relationship invariant between `.o` and `.m`

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invariant broken 

but only temporarily 

Program

**Tolerate “temporary” violation with** 

# Safe but not type safe ...

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class Callback:
    var sel: Str
    var obj: Obj

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# Is Fissile effective at proving reflective call safety?

- Fissile analyzes Objective-C source
- 9 benchmarks (6 libraries + 3 apps)
  - 1,000 to 176,000 lines of code
  - 461,000 lines in total
- Type annotations
  - seeded with 76 `respondsTo` in system libraries
  - needed only 136 annotations in benchmarks (total)

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Big Deal: makes IDE integration possible

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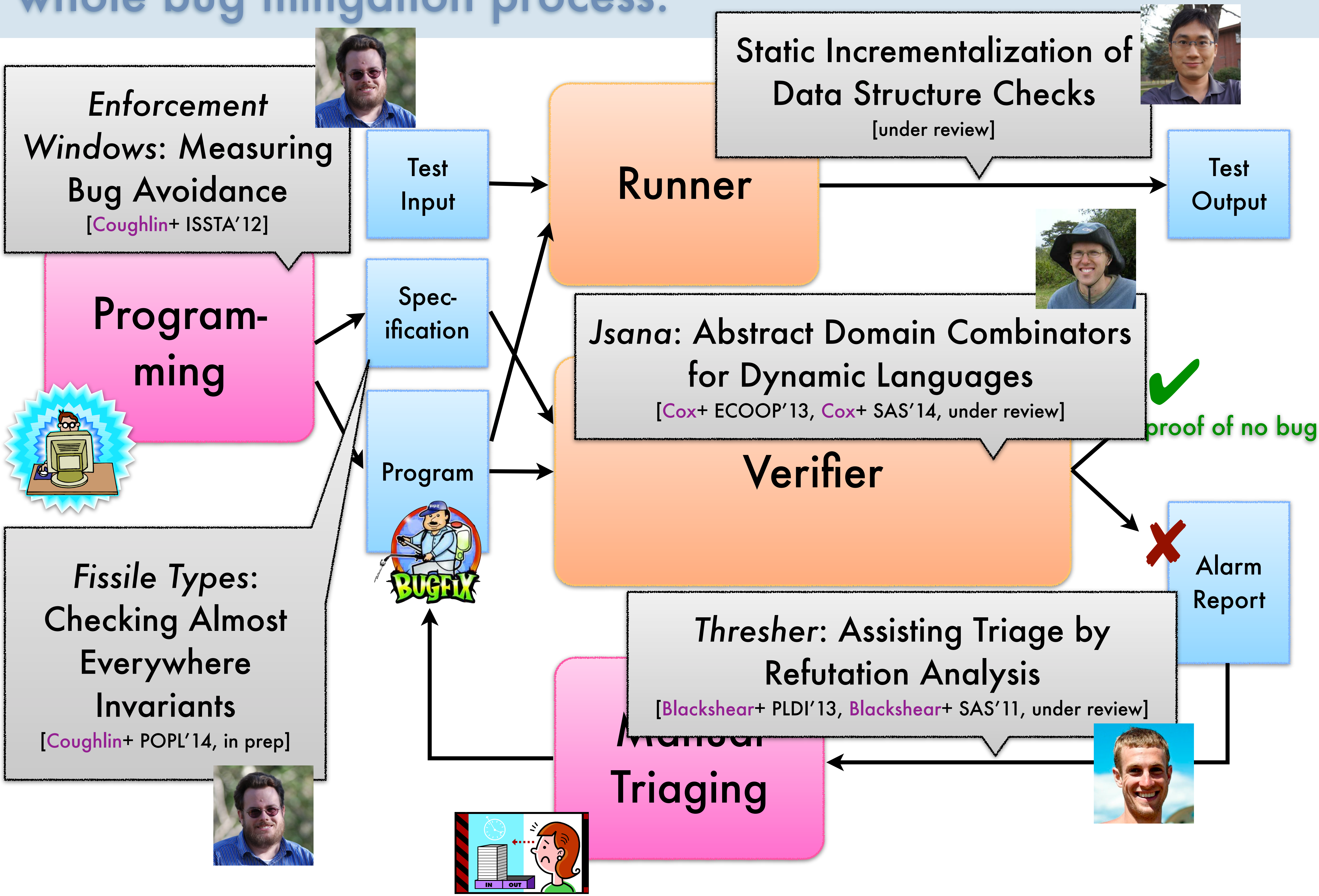

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