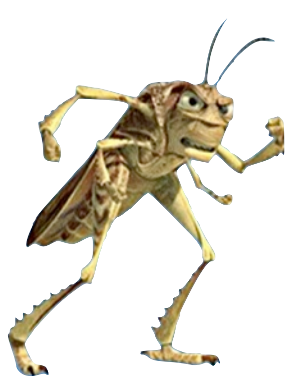



Cooperative Program Analysis

Bor-Yuh Evan Chang
University of Colorado Boulder

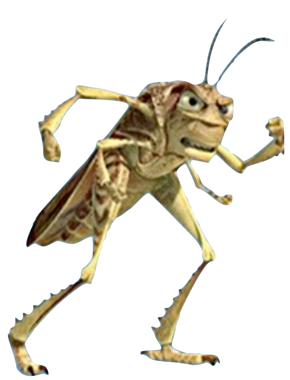


October 3, 2013

PLV




A program analysis story ...




A380

Software is everywhere and varying more and more

traditional

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traditional

mobile

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mobile

cloud

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mobile

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cyberphysical

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cyberphysical

Software is everywhere and varying more and more

Software is getting more and more complex

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mobile

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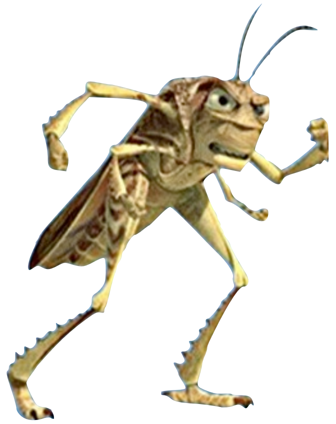
Software is getting more and more complex


HELP!

1980s: Bug in Therac-25 kills



1980s: Bug in Therac-25 kills

2000s: Conficker worm costs $9.1 billion in damages

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2000s: Conficker worm costs $9.1 billion in damages

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

Program Analysis for Formal Verification

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The Ugly, Hidden Truth

Program Analysis for Formal Verification

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

The Ugly, Hidden Truth

Program Analysis for Formal Verification

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

Uncooperative Program Analysis?

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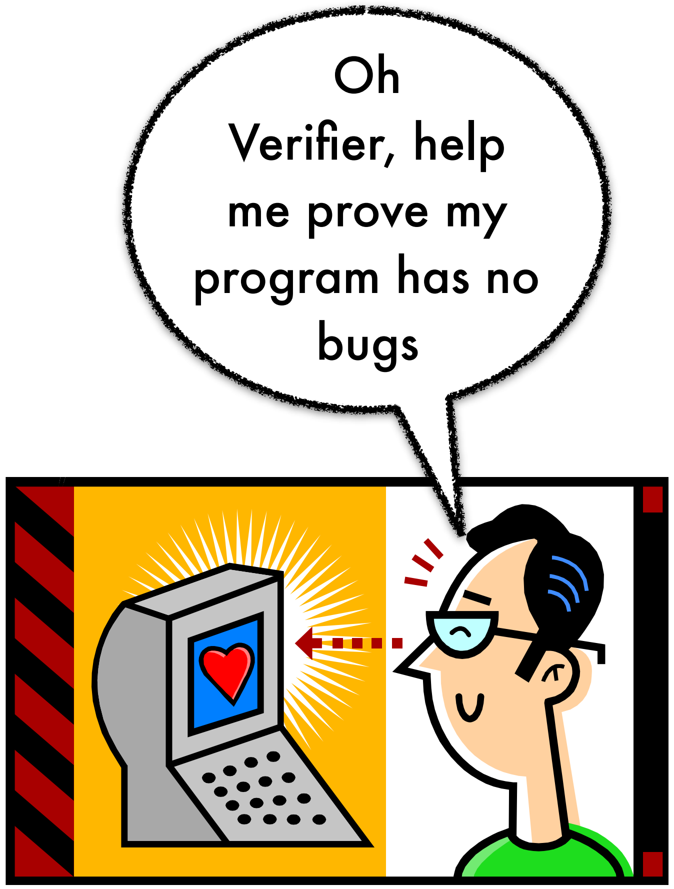

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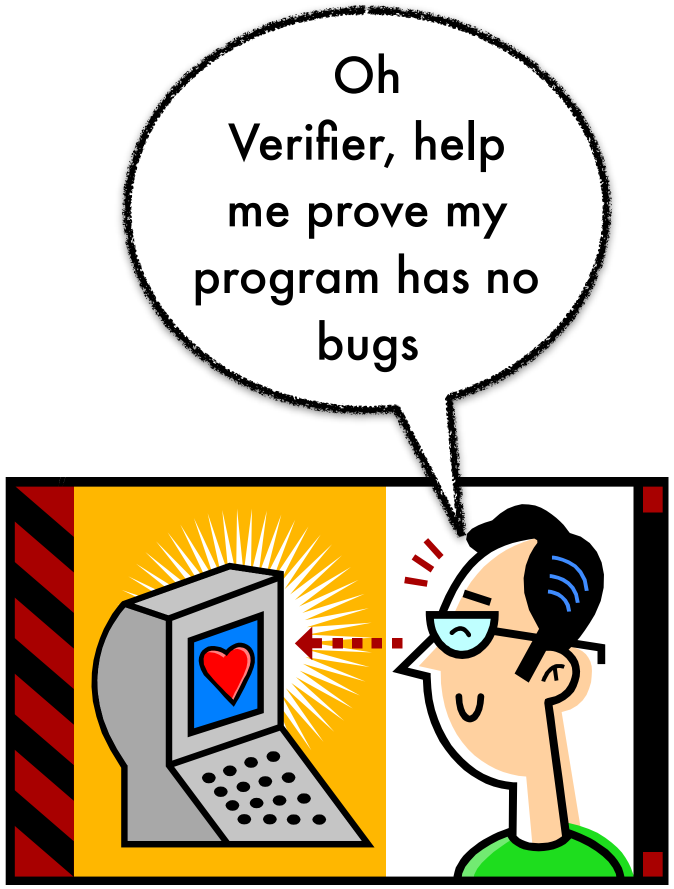

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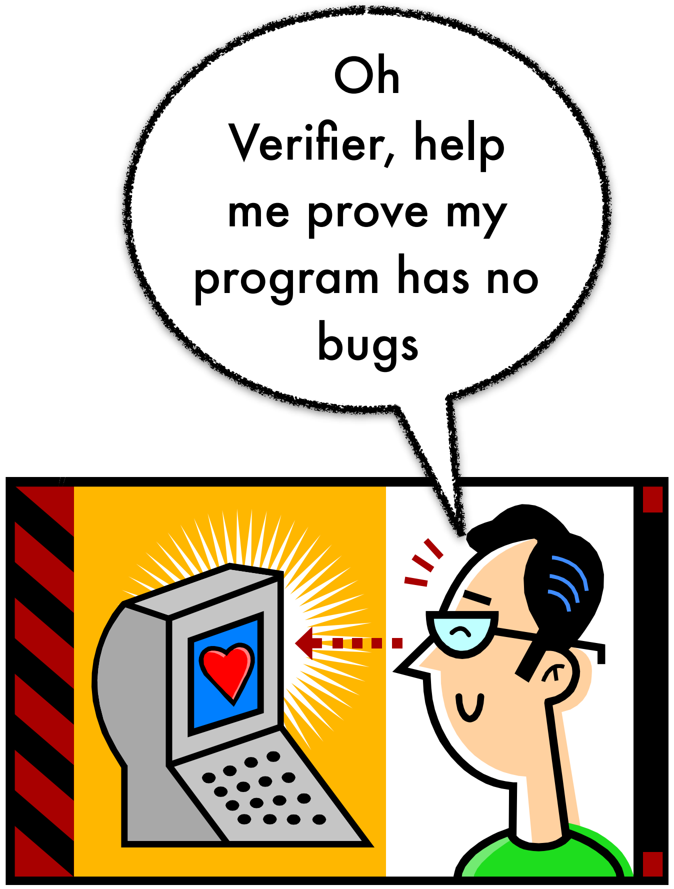

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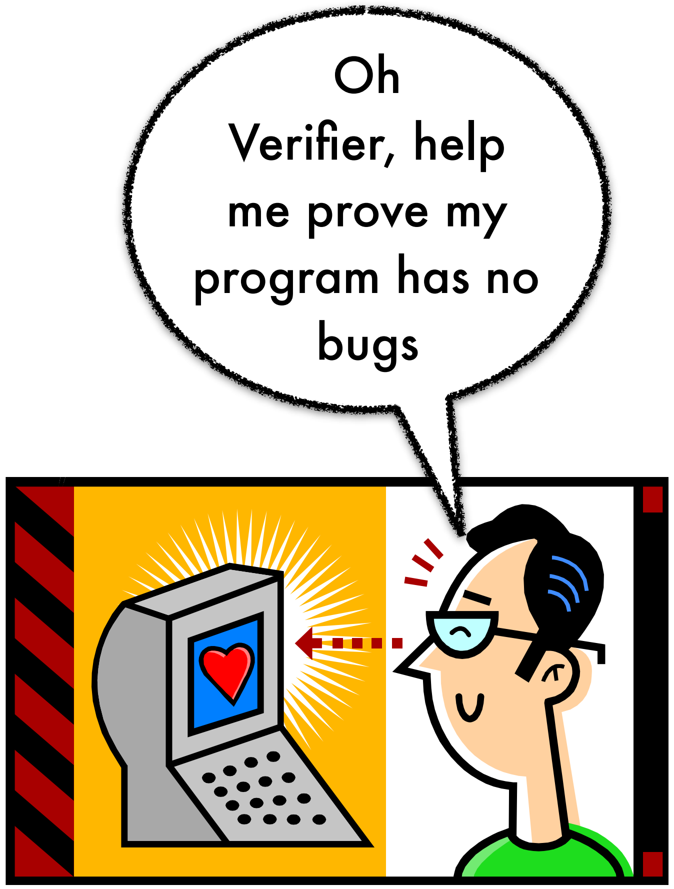
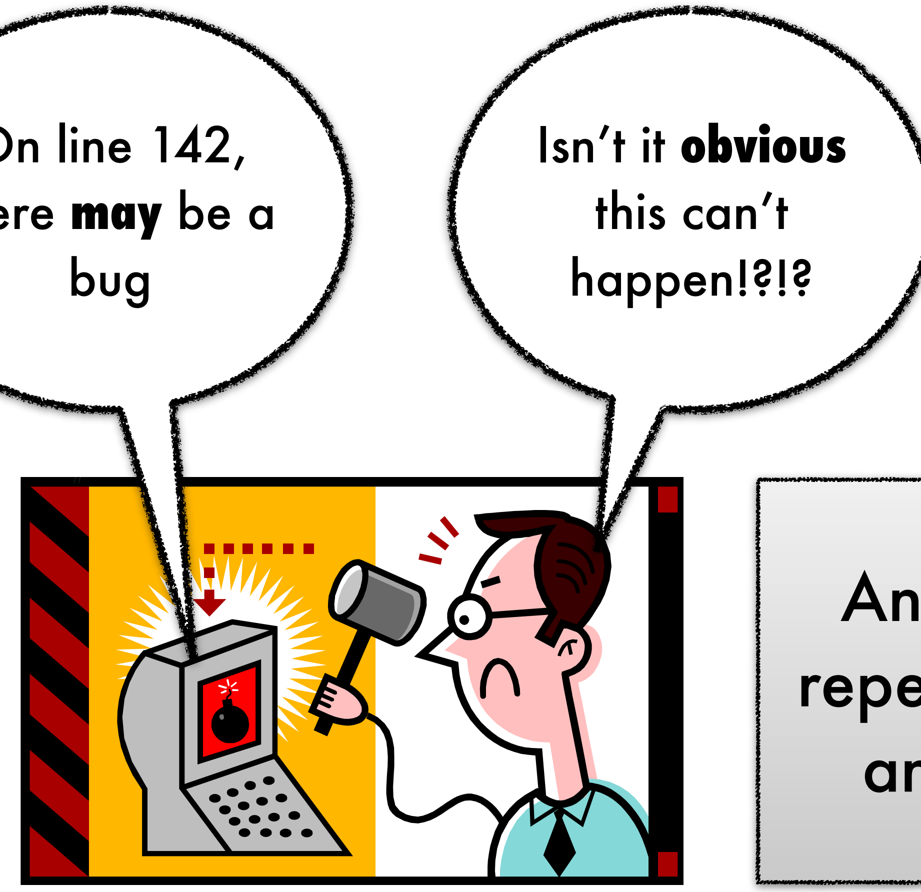
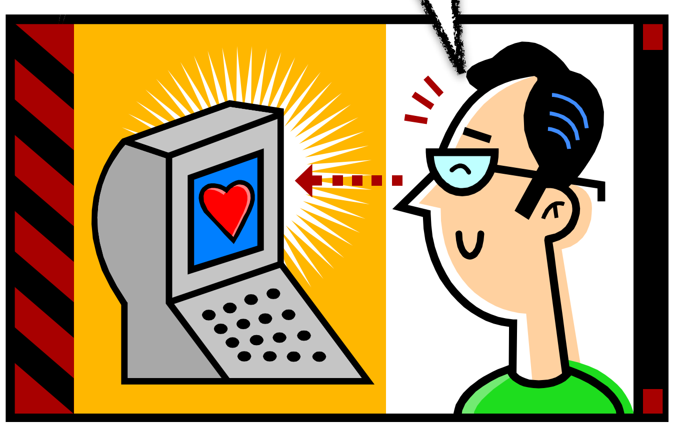




And noisily repeated over and over!

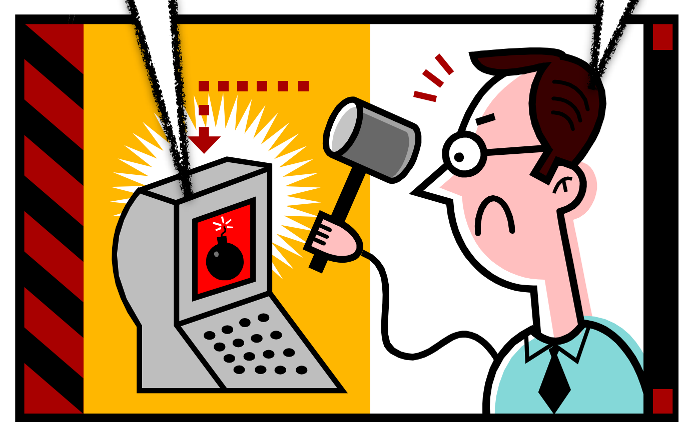
Uncooperative Program Analysis?

Oh
Verifier, help
me prove my
program has no
bugs



On line 142,
there **may** be a
bug

Isn't it **obvious**
this can't
happen!?!?



And noisily
repeated over
and over!

The well-known **false alarm** problem

Uncooperative Program Analysis?

Oh
Verifie
me pro
program
bug

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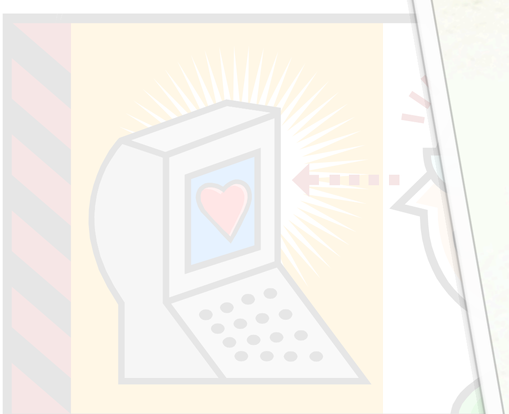
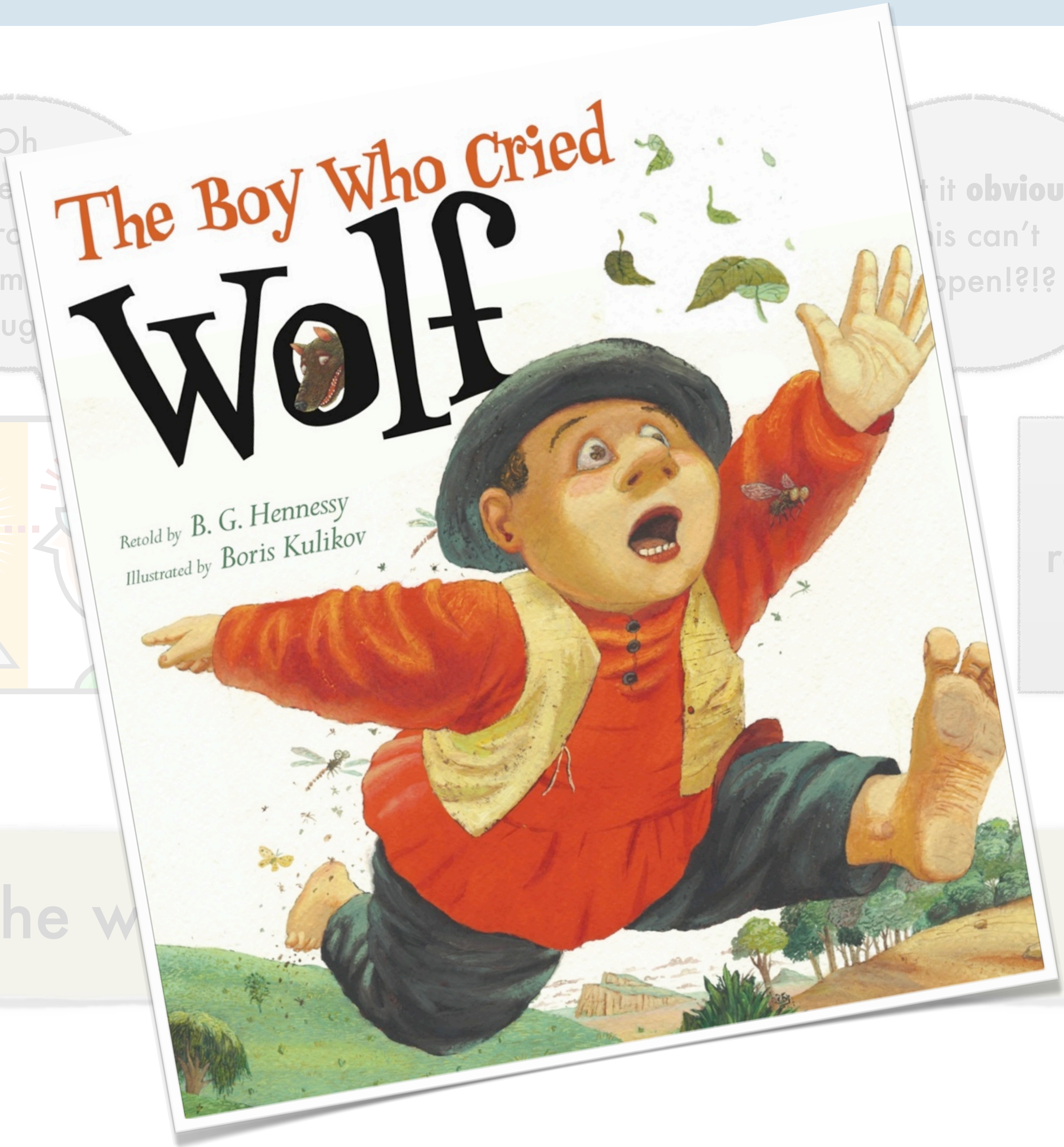
is can't
pen!?!?





And noisily repeated over and over!

The w

"[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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The traditional approach to the false alarm problem focuses on improving the verifier.

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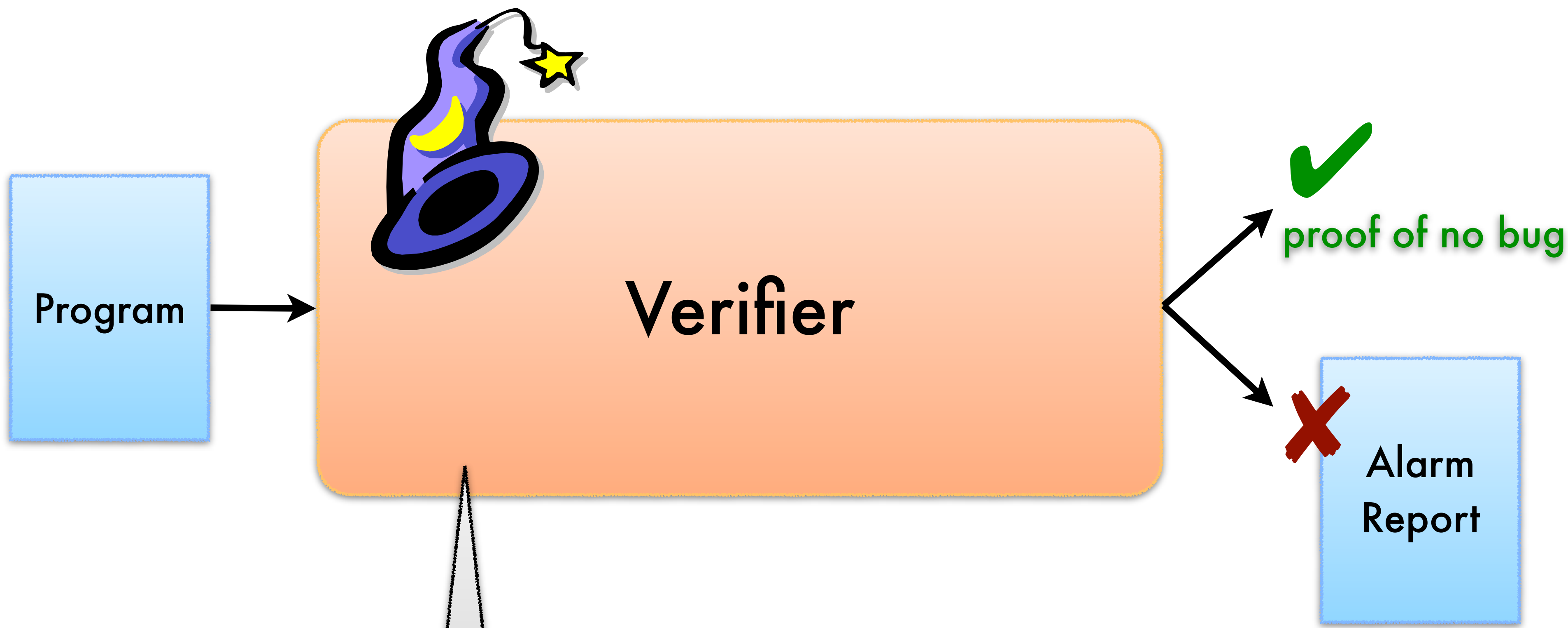

Redesign the verifier with more magic to hopefully reduce the number of false alarms

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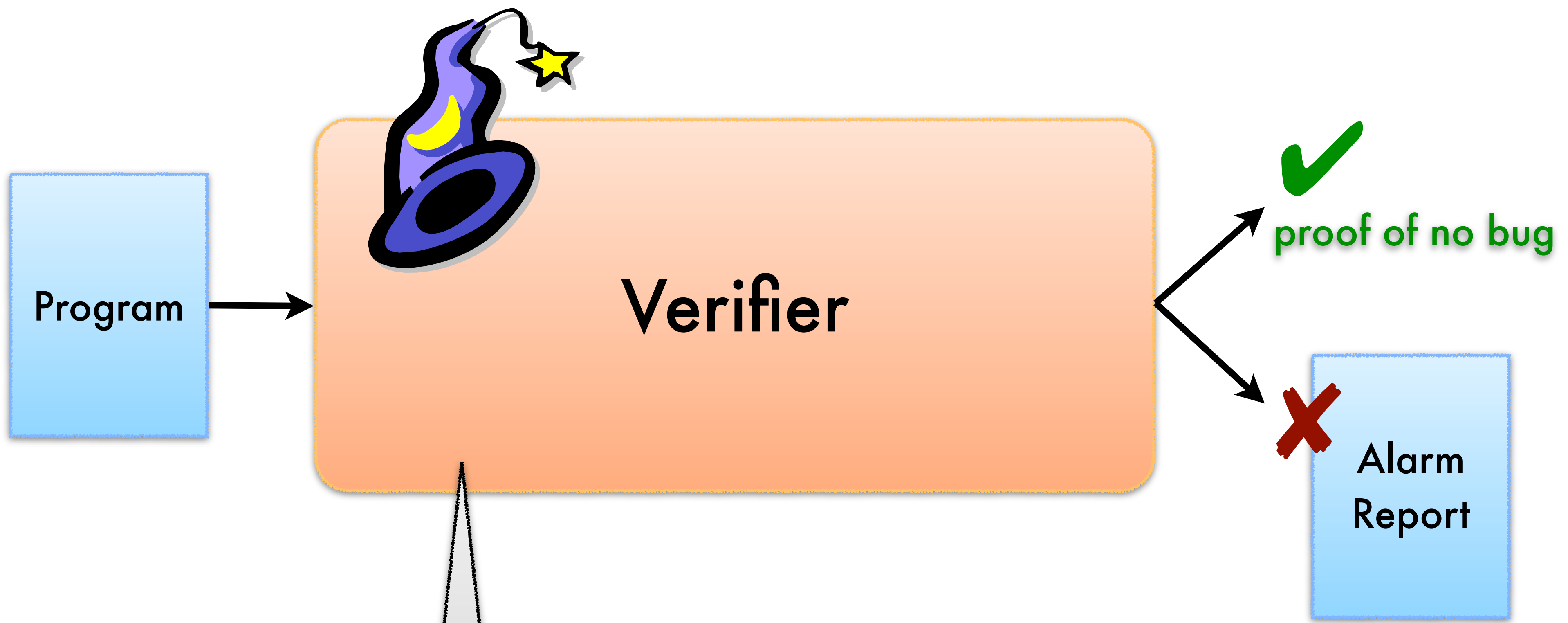

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But it can never be perfect (undecidability)

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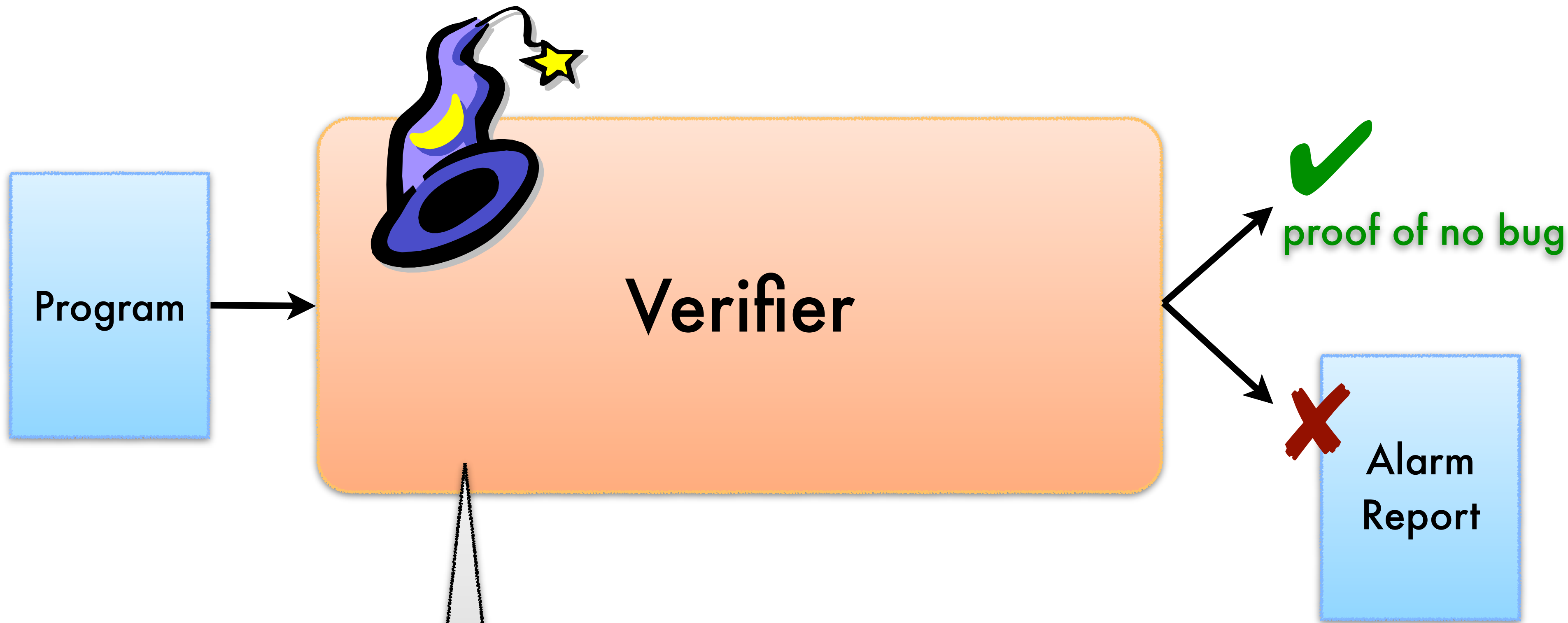
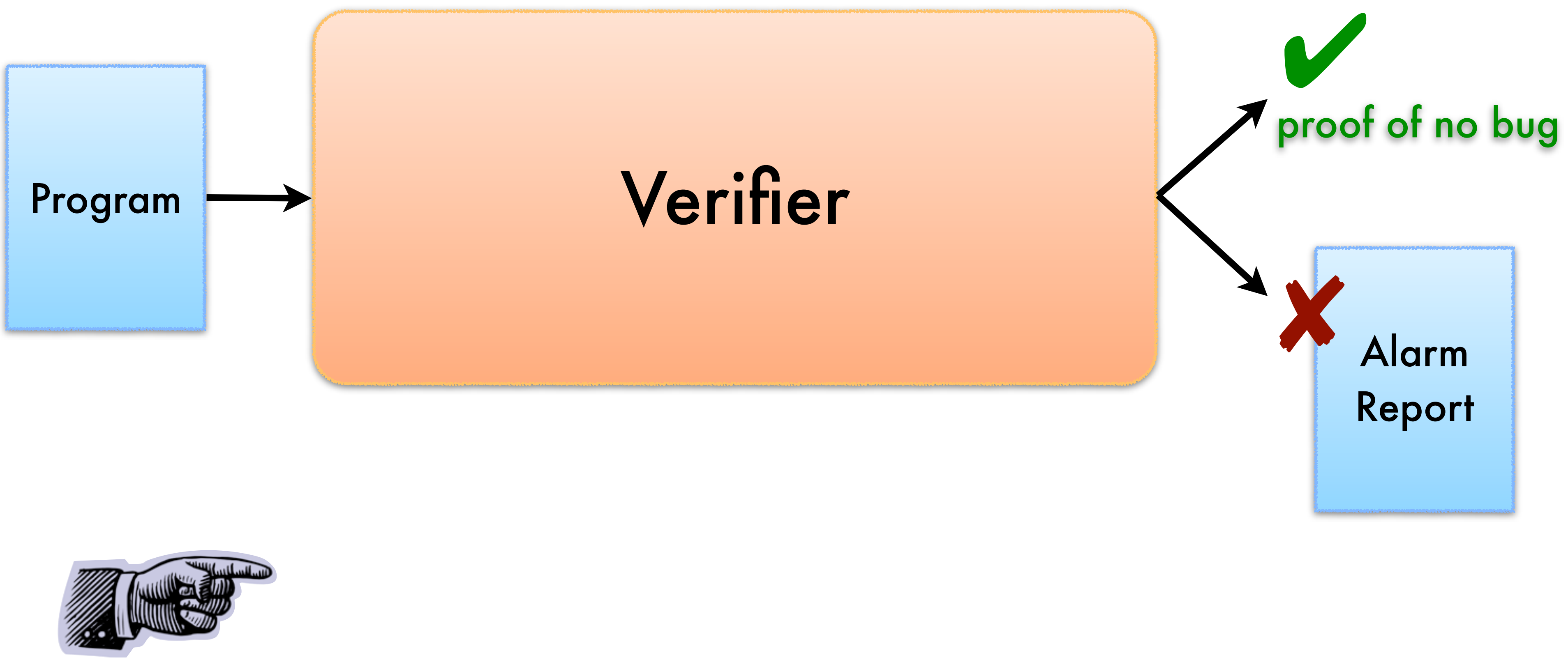


Redesign the verifier with more magic to hopefully reduce the number of false alarms

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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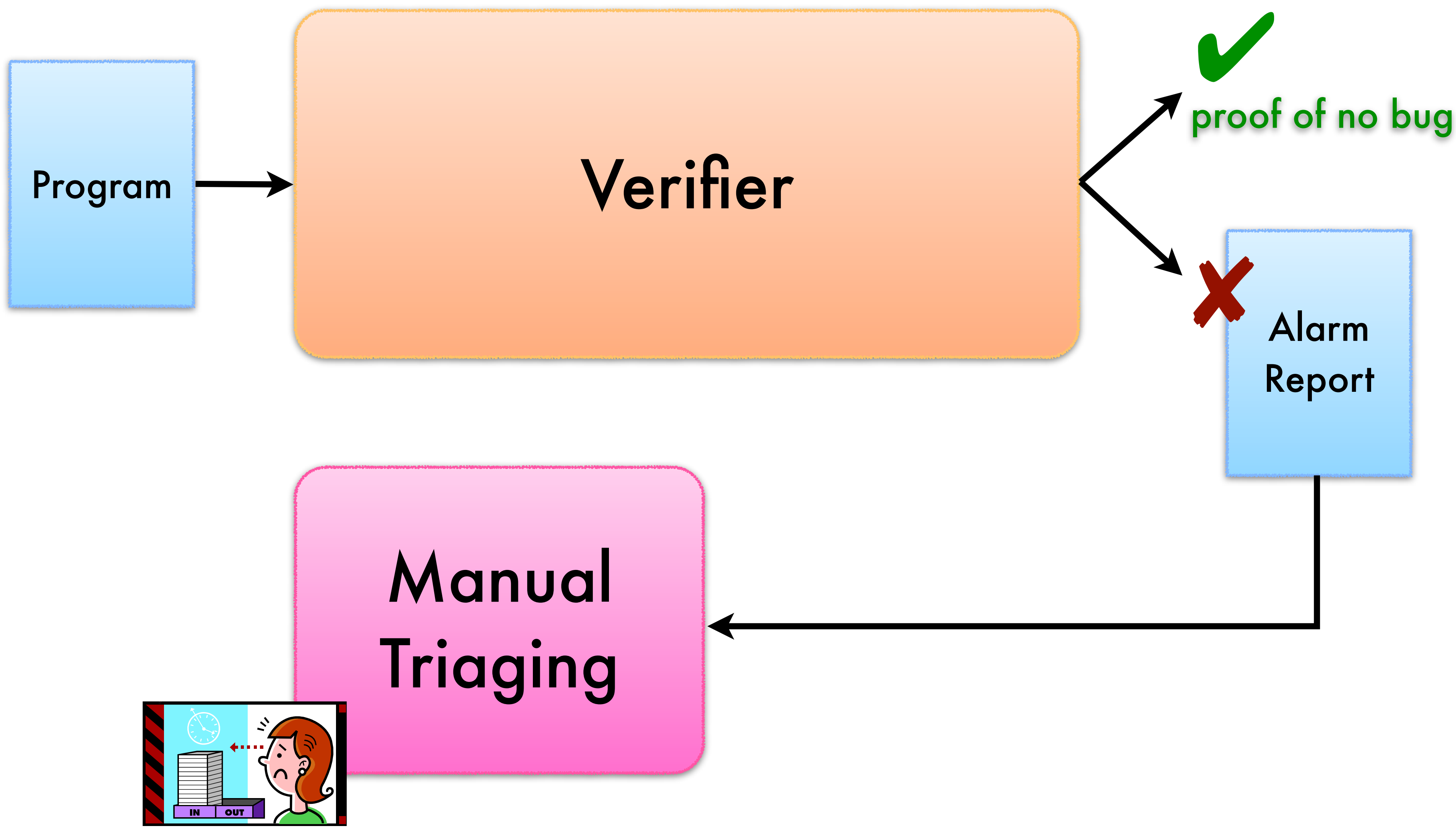

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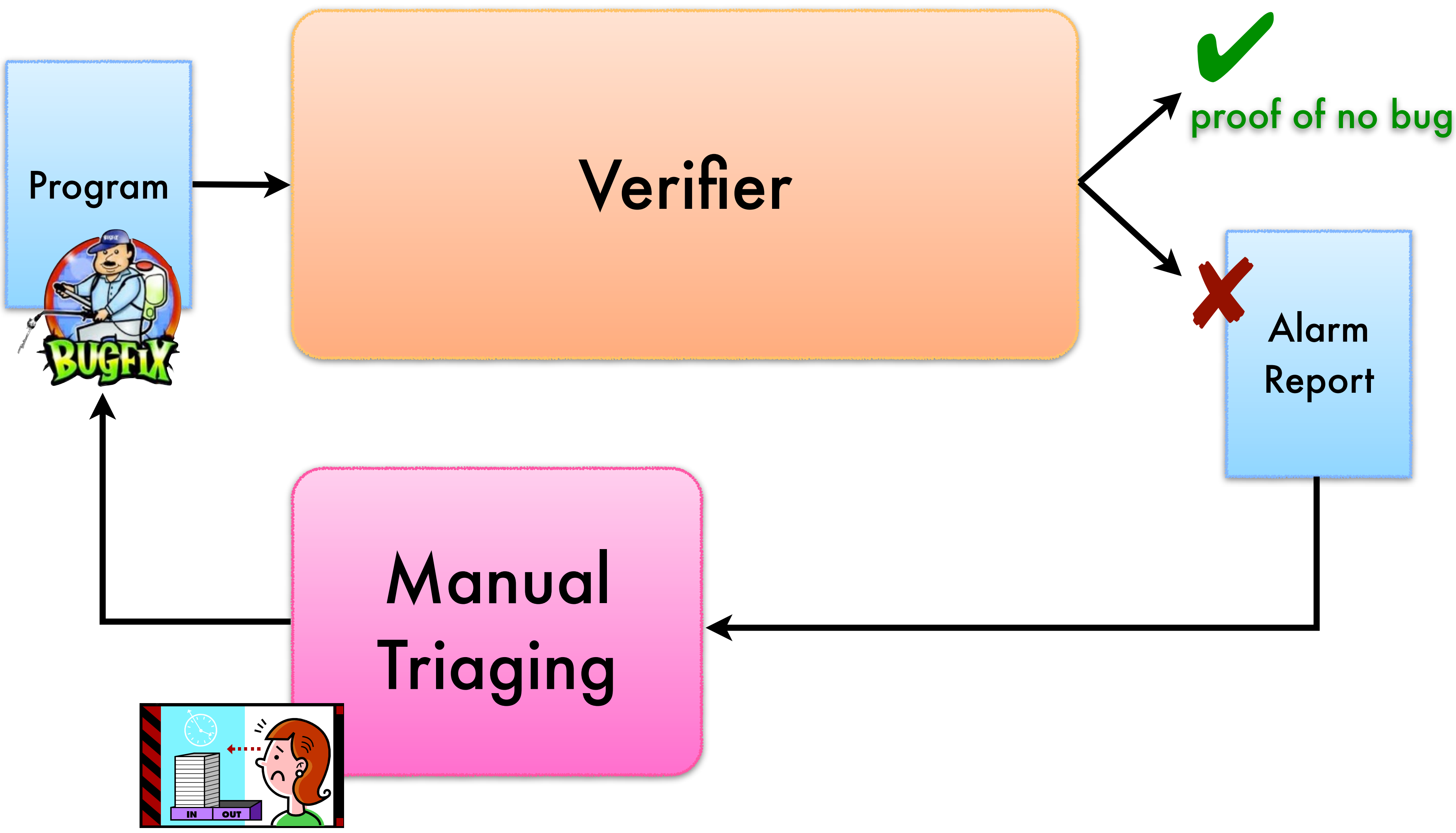

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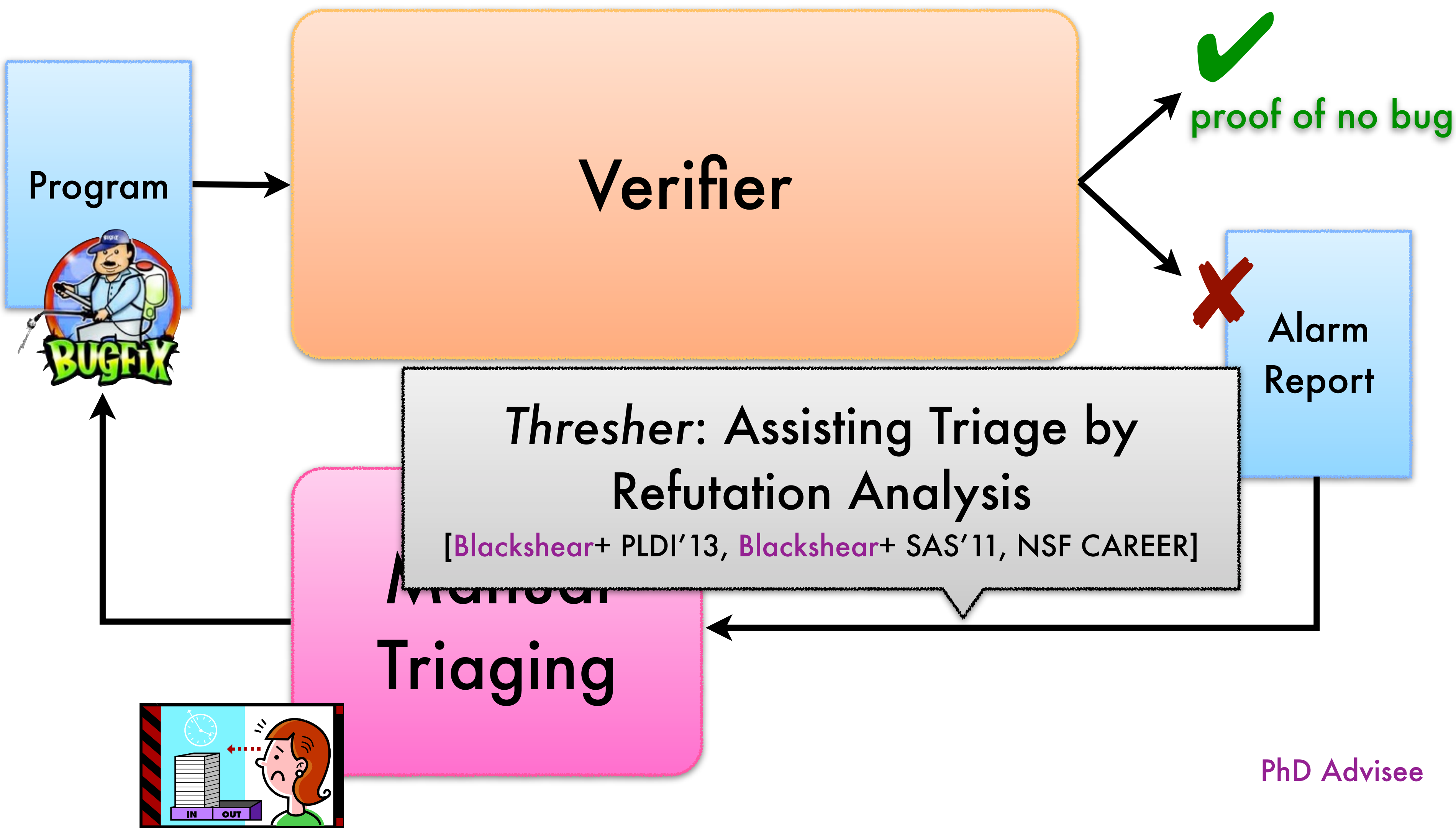

PhD Advisee

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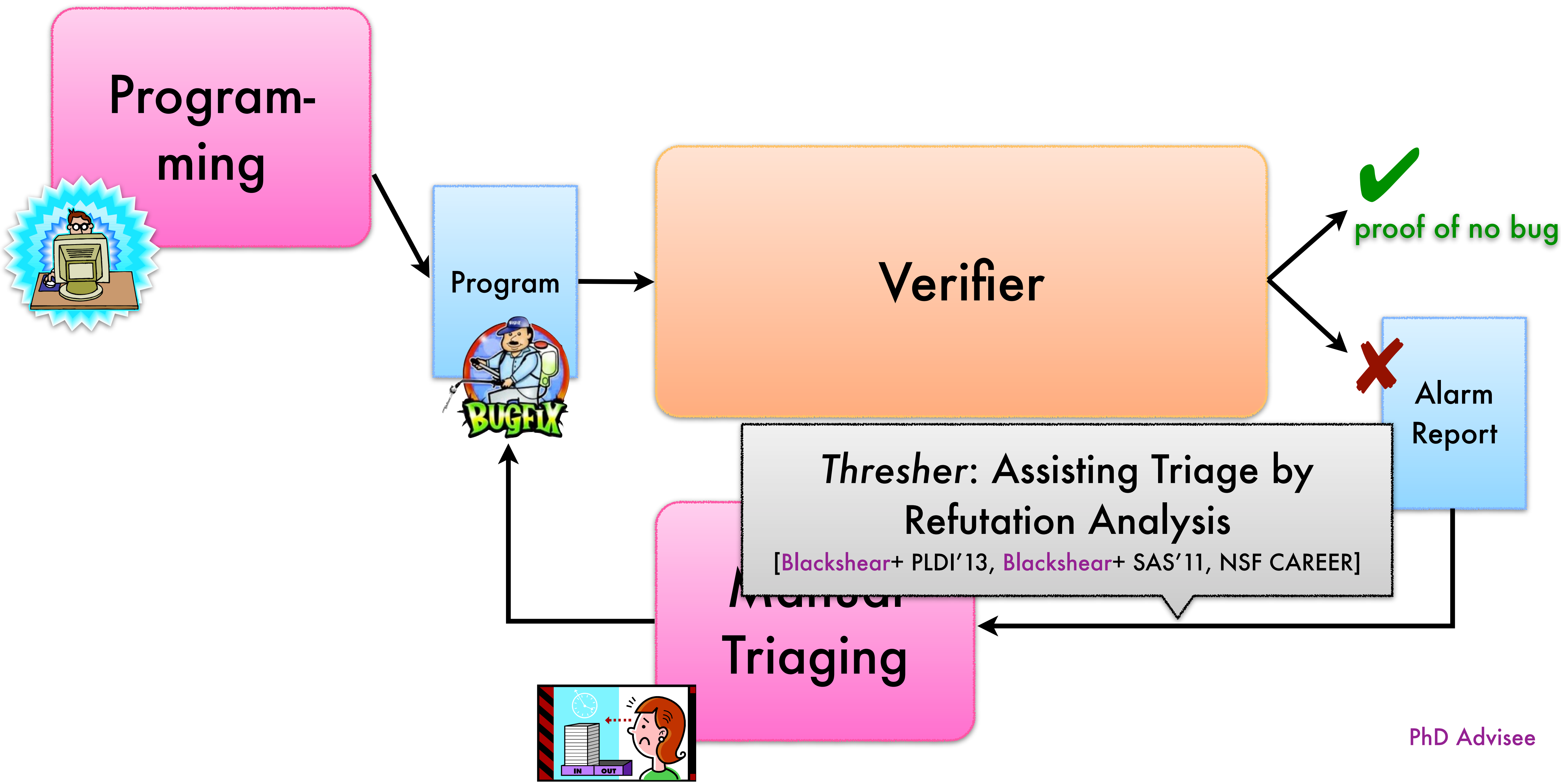

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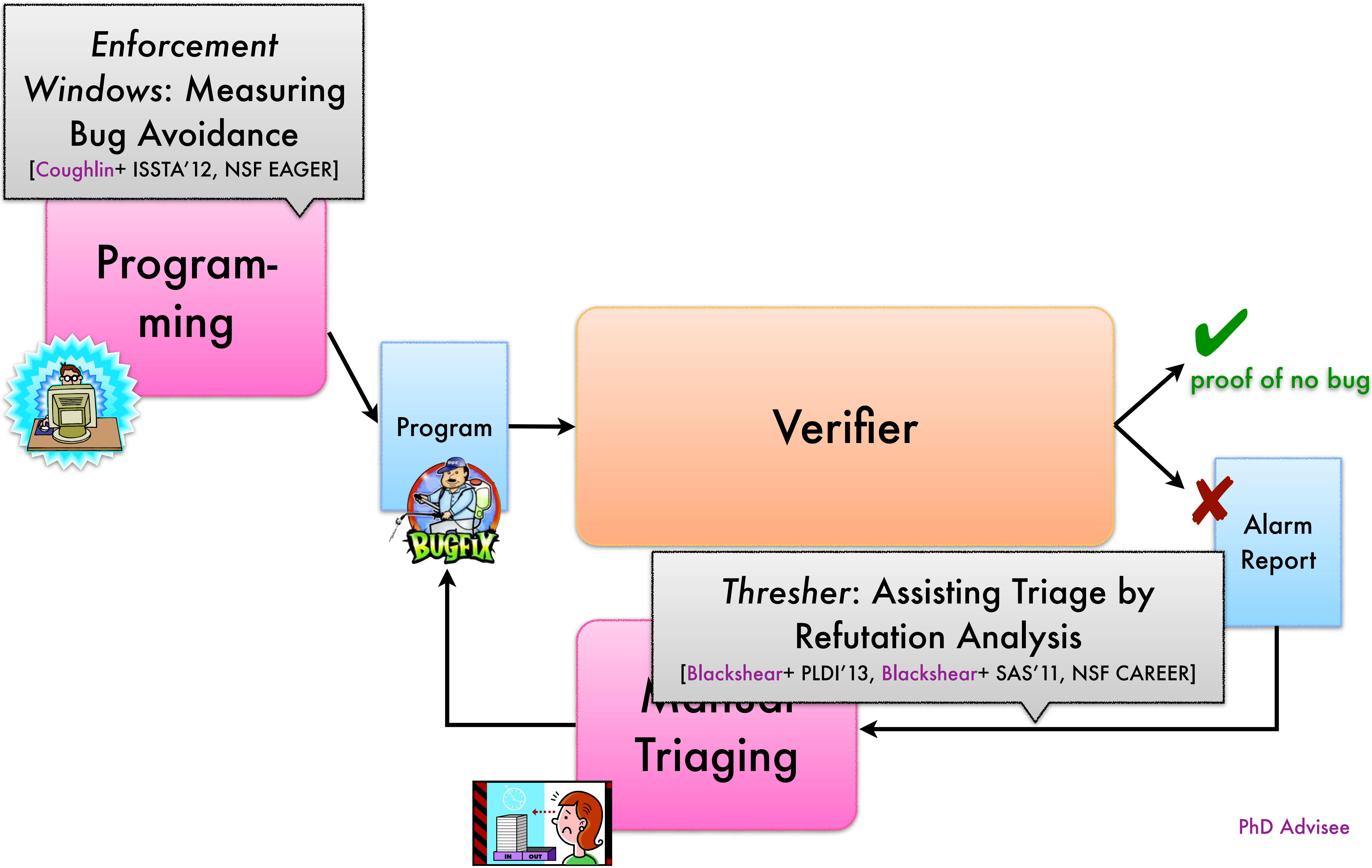

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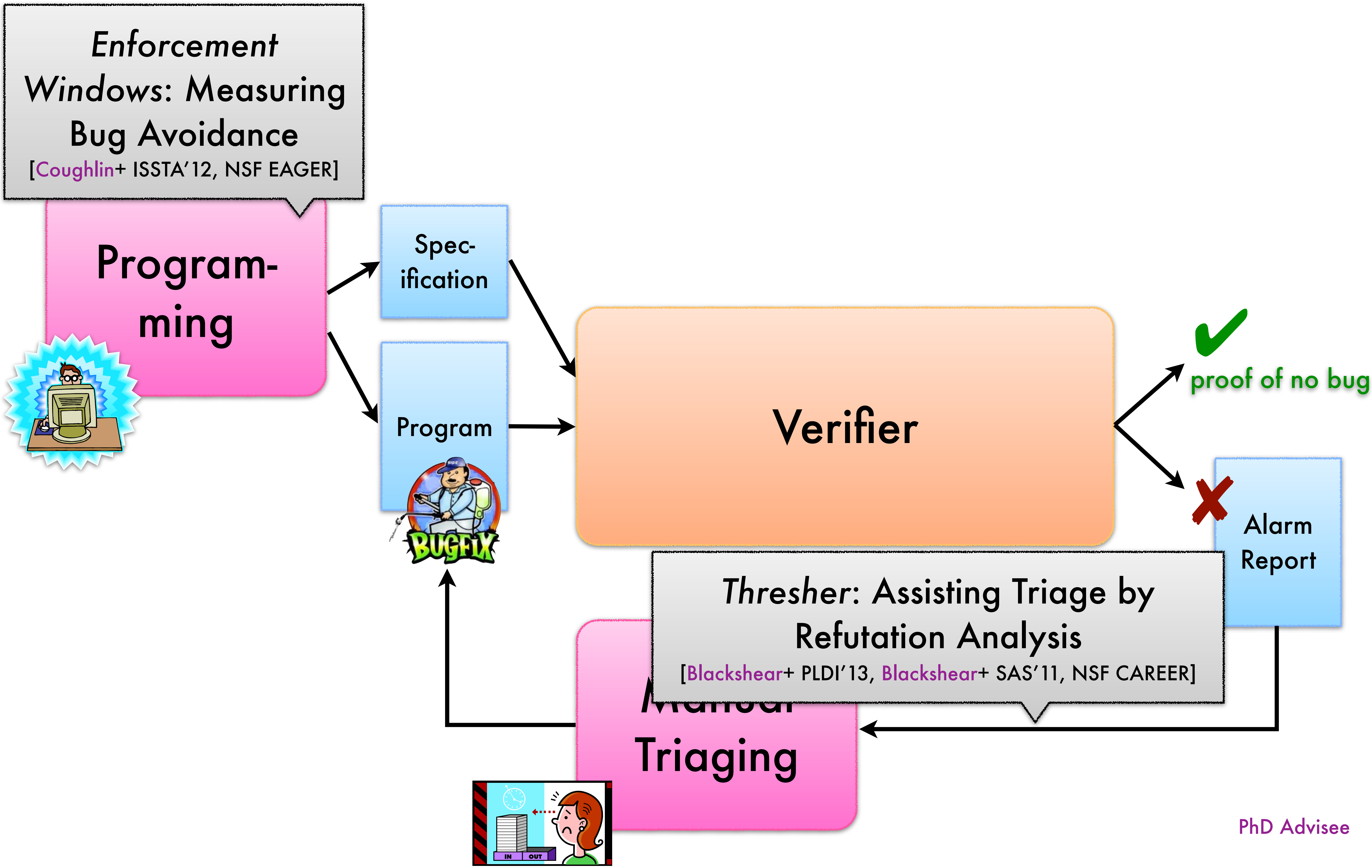

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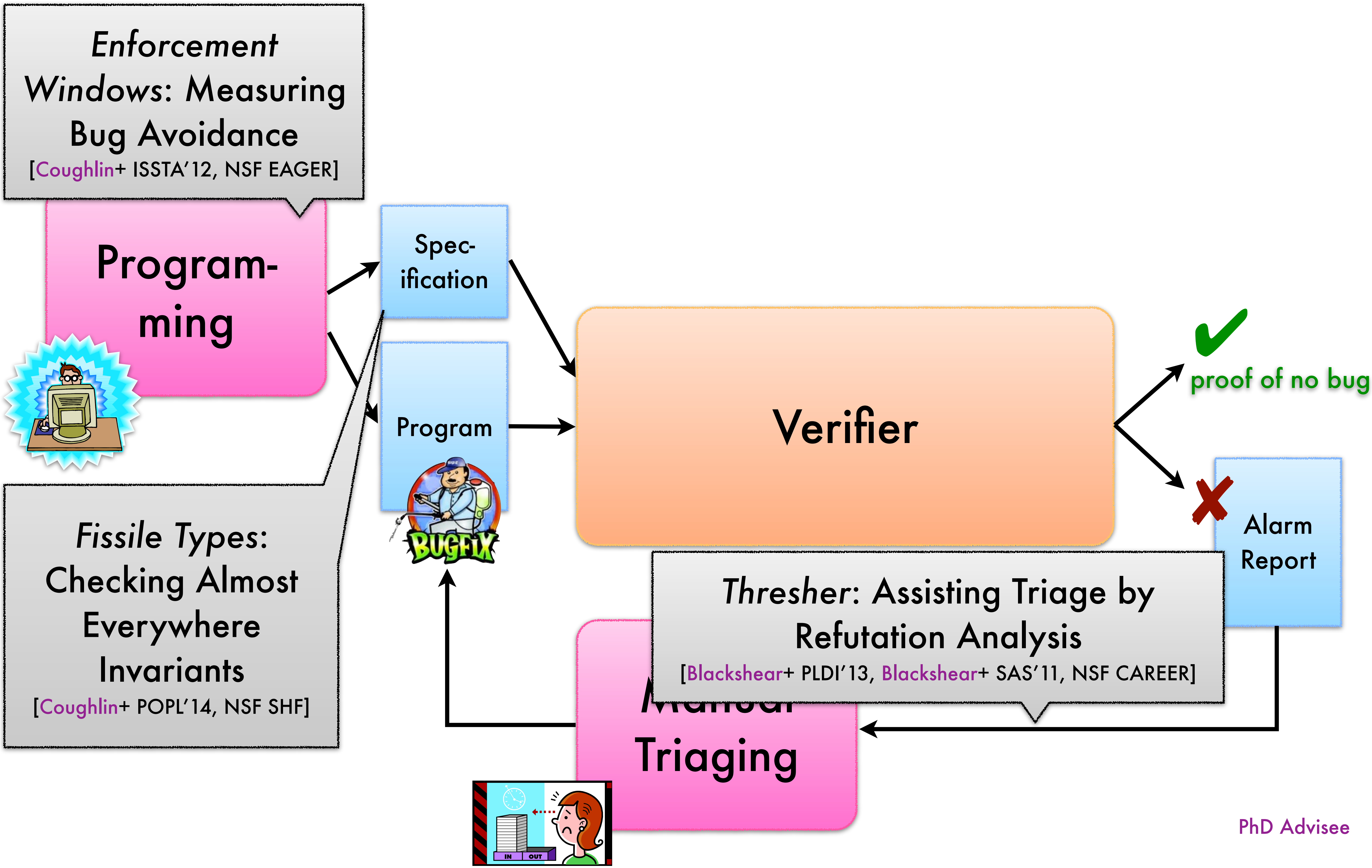

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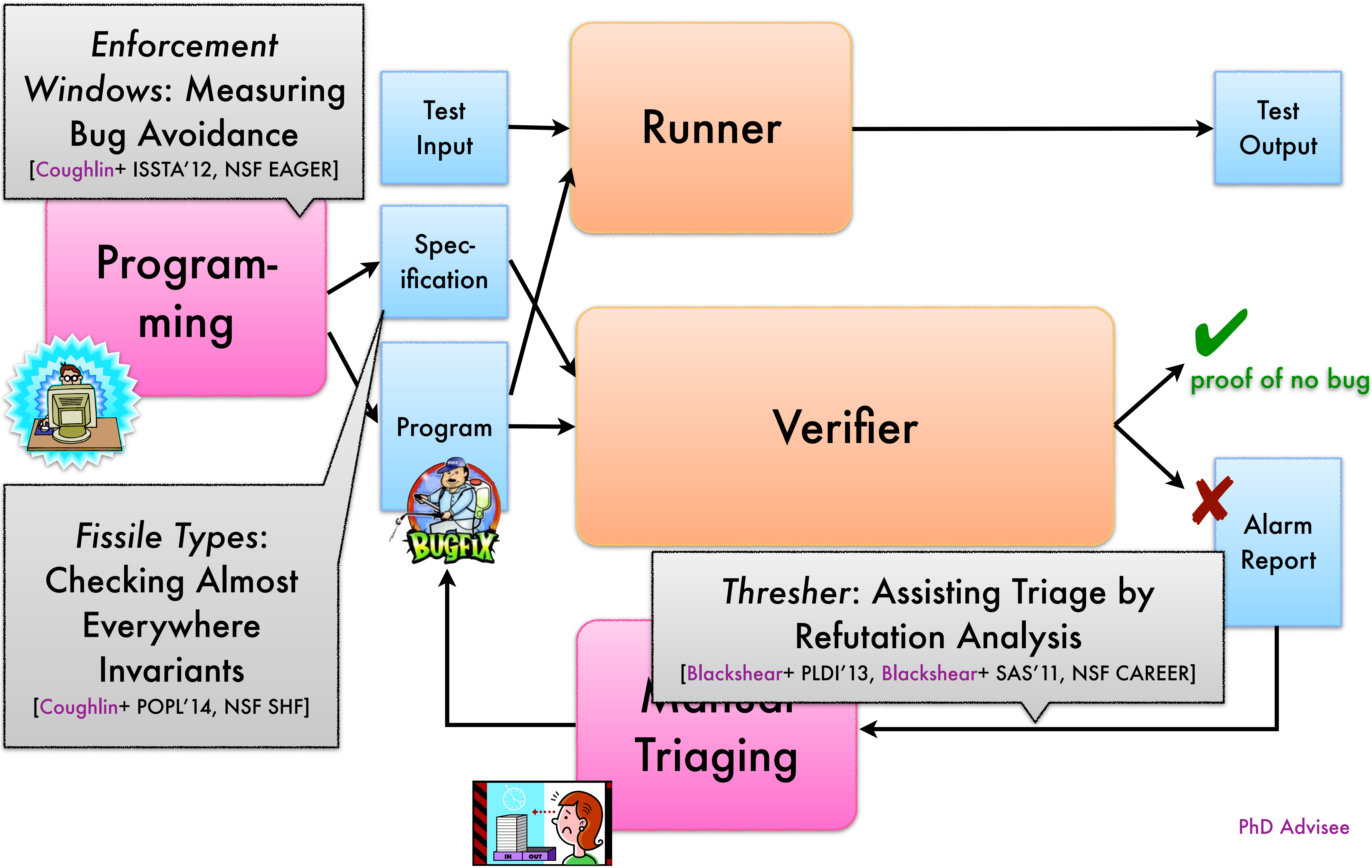

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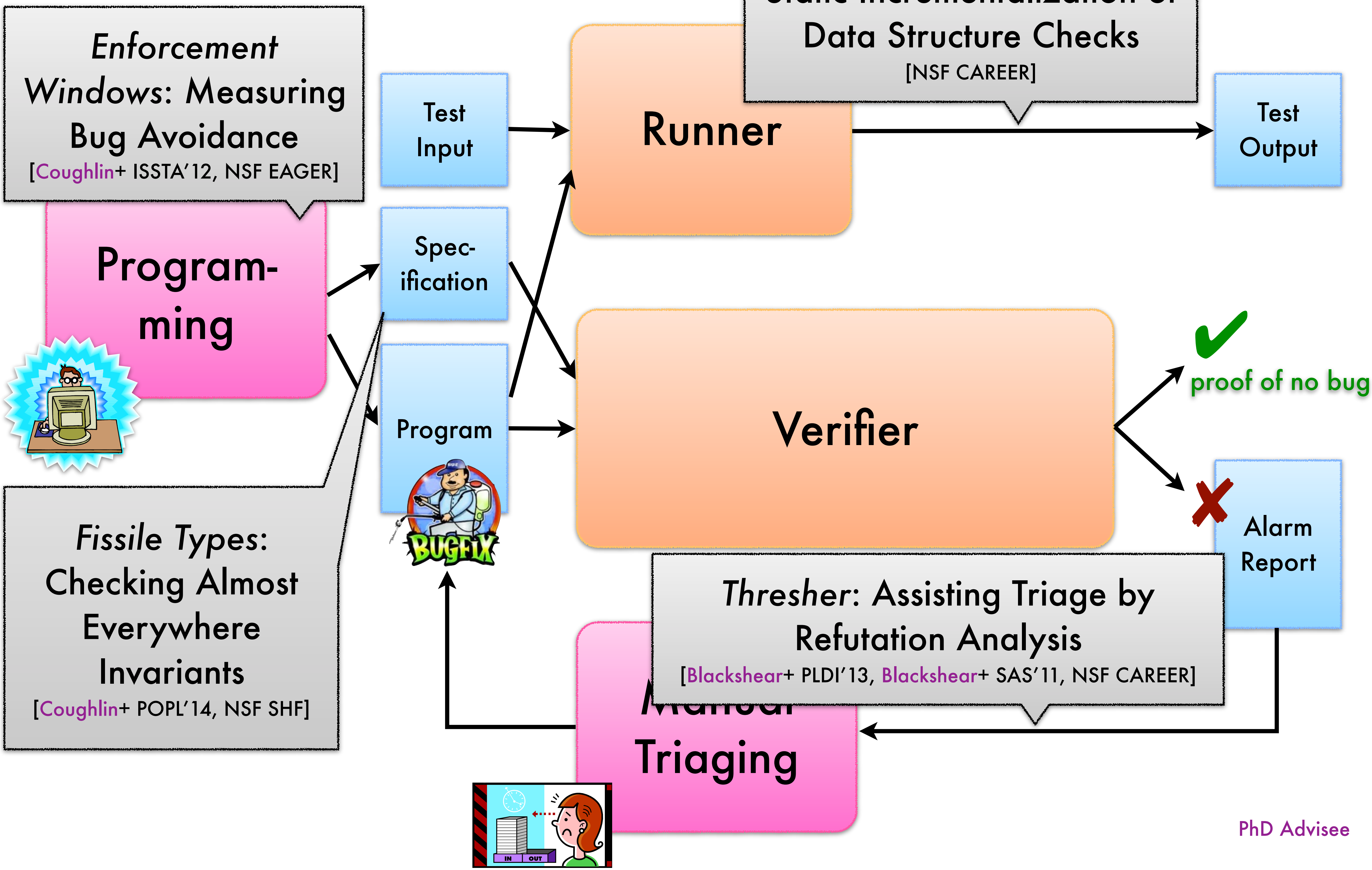

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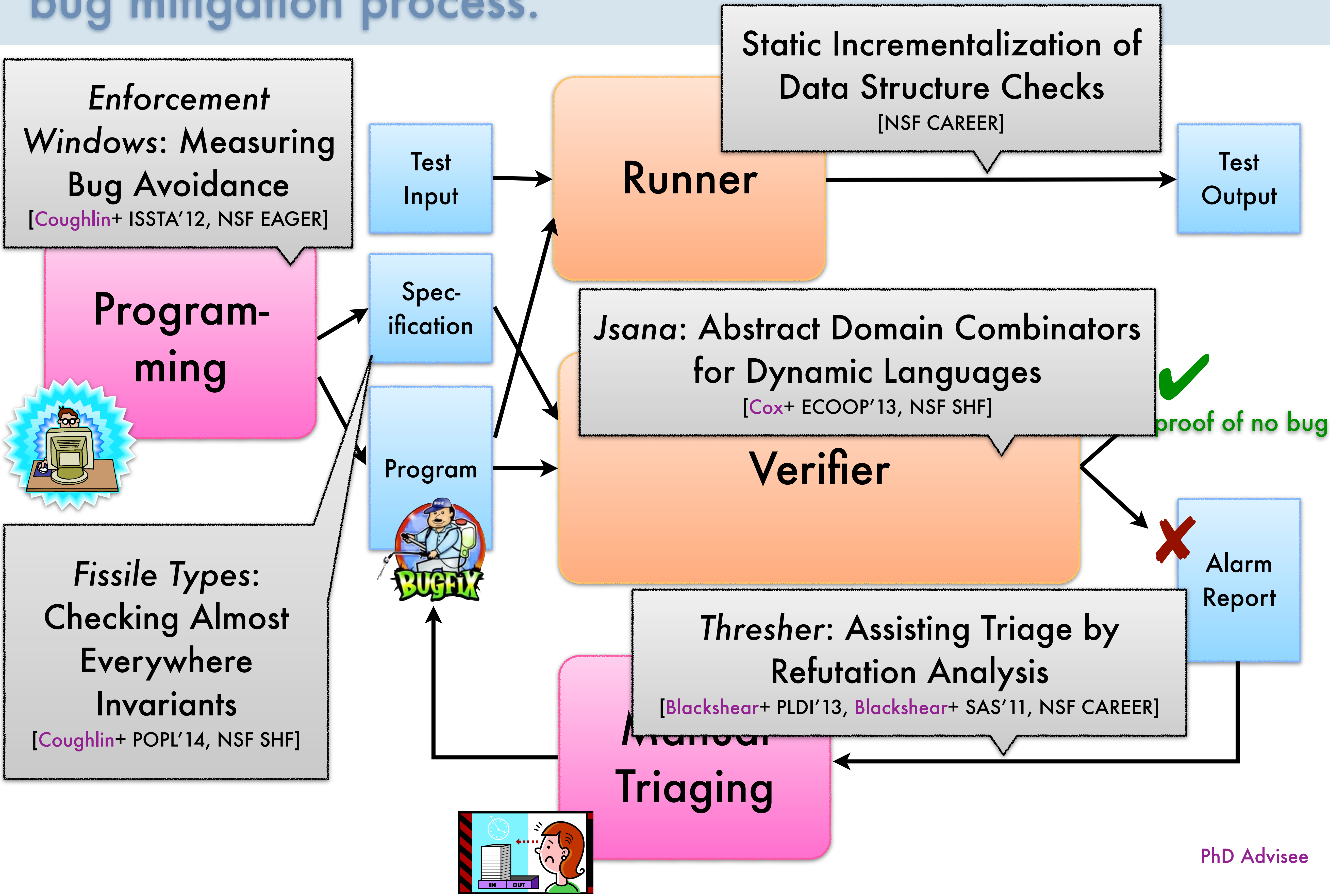

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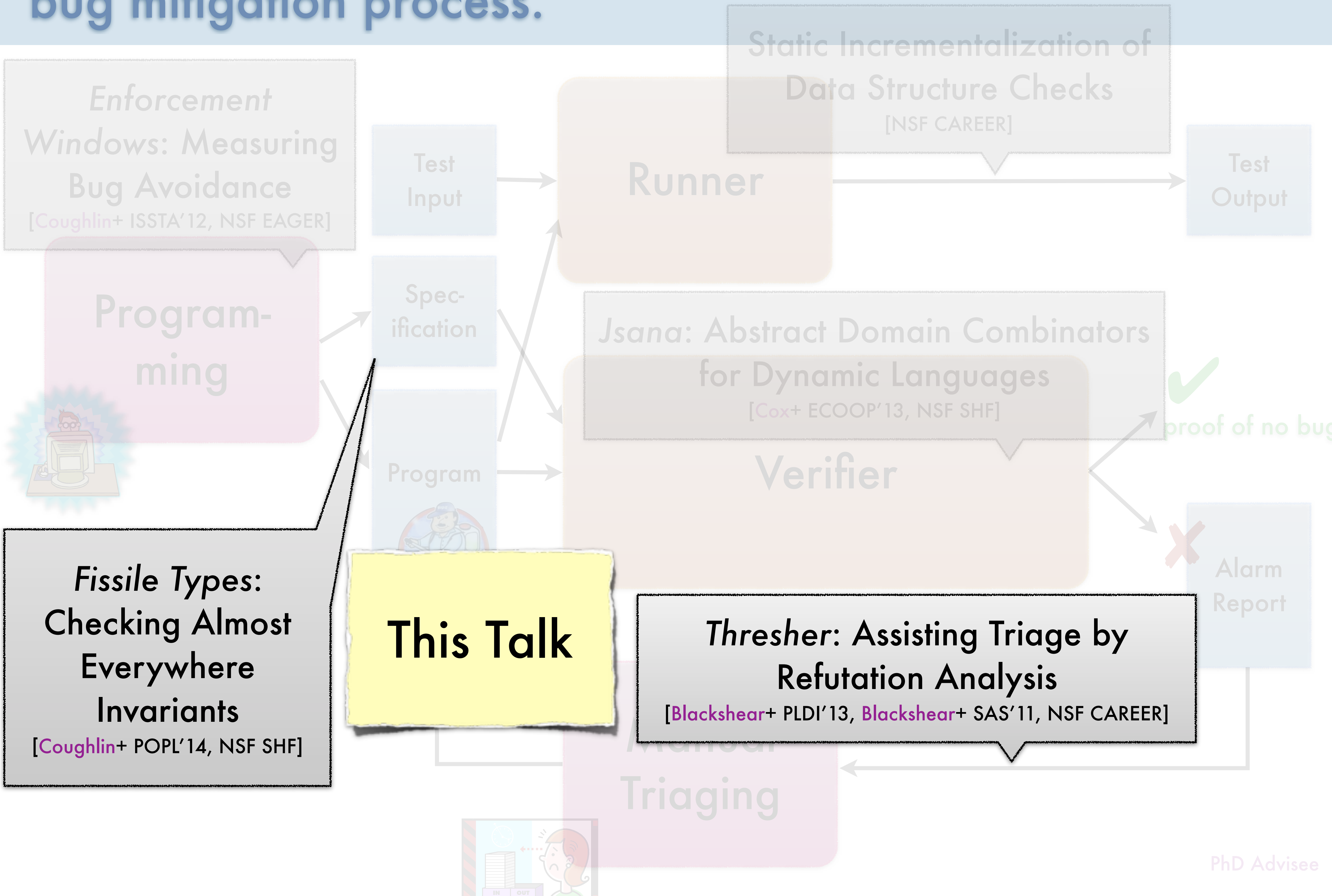

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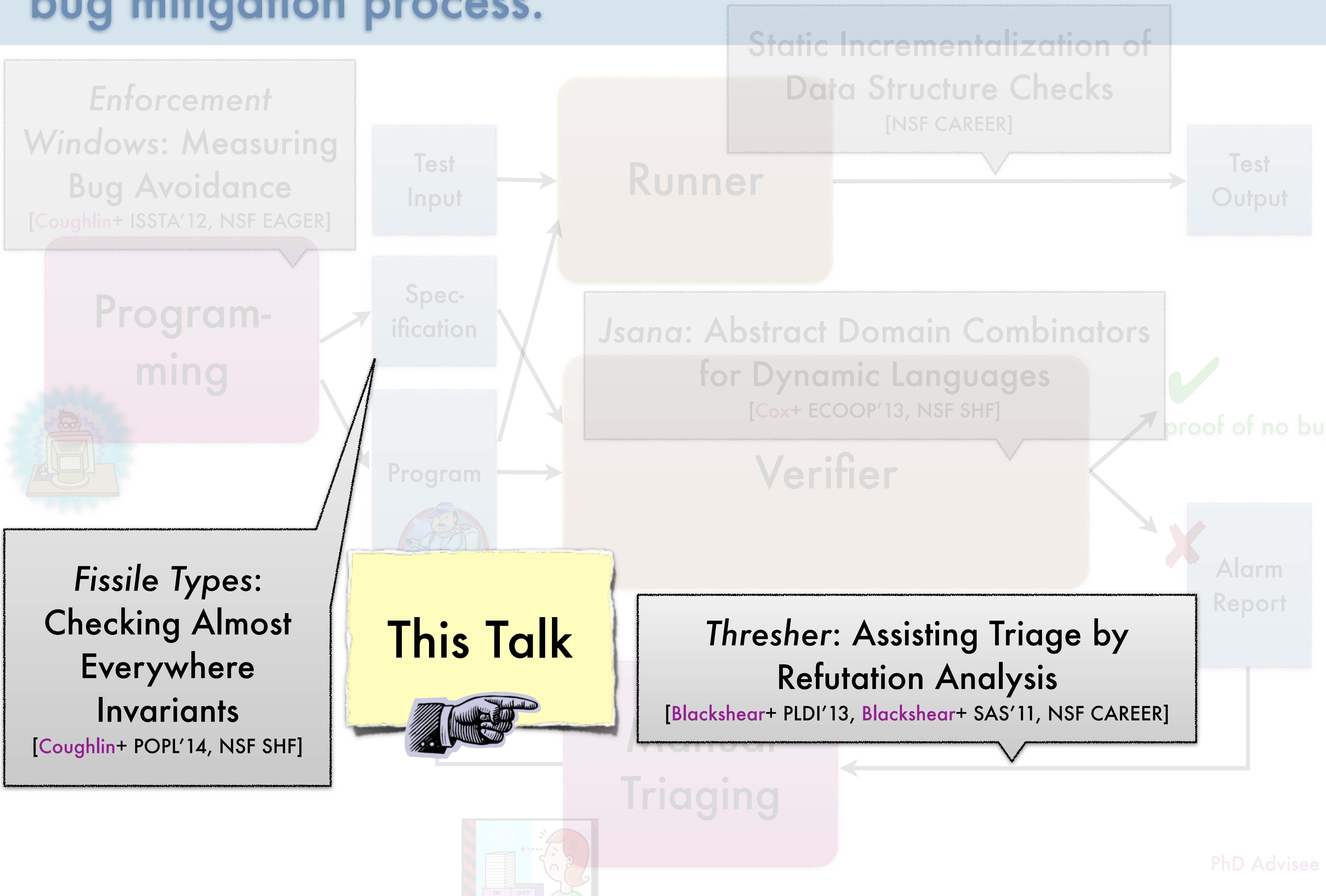

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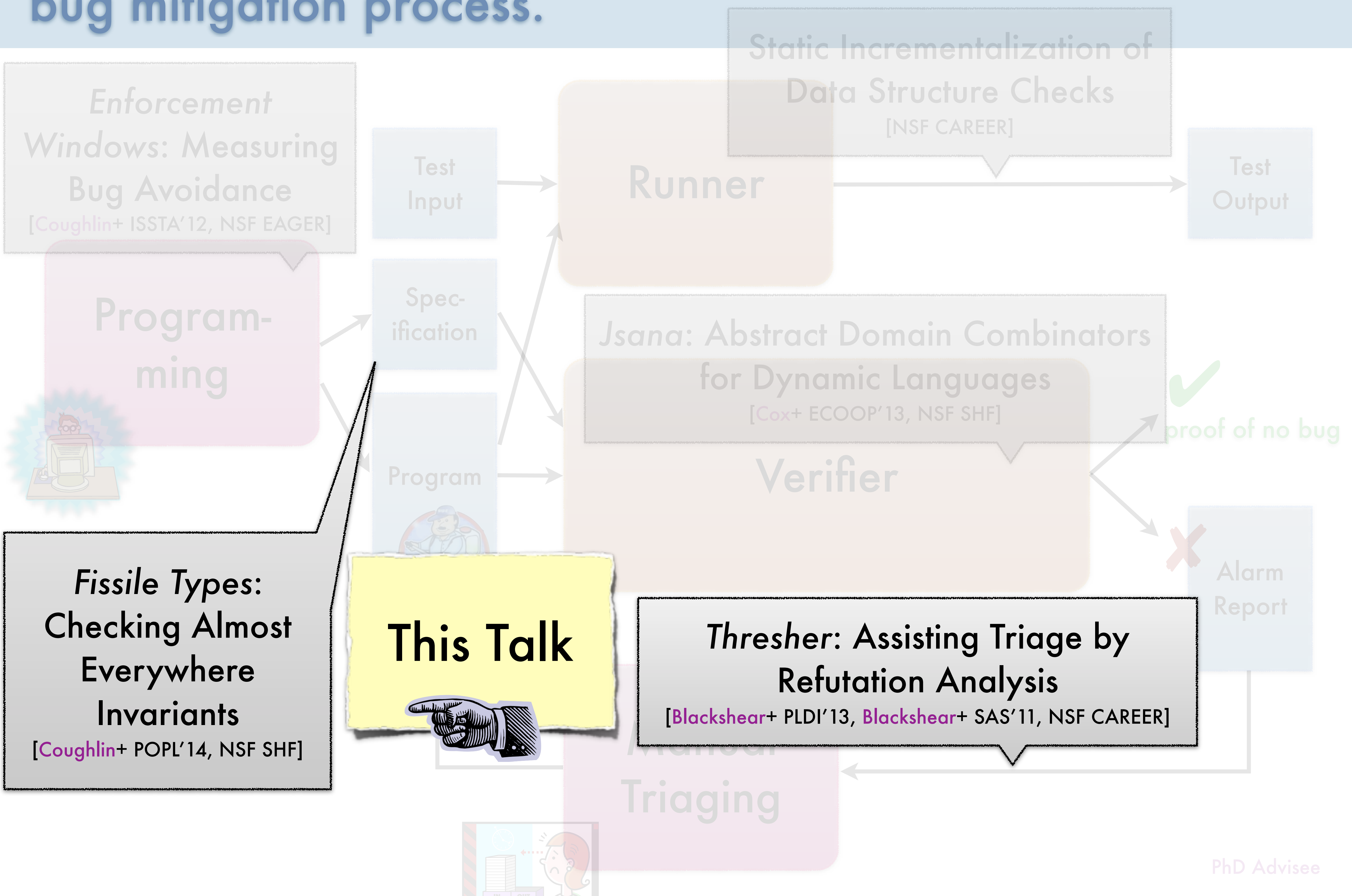

Fissile Types: Checking Almost Everywhere Invariants
[Coughlin+ POPL'14, NSF SHF]

This Talk

Thresher: Assisting Triage by Refutation Analysis
[Blackshear+ PLDI'13, Blackshear+ SAS'11, NSF CAREER]

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
- Application: Find memory leaks and eliminate crashes in Android

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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
- Application: Prevent "MethodNotFound" errors in Objective-C (MacOS/iOS)

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Thresher: Precise Refutations for Heap Reachability

What are heap reachability queries?

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

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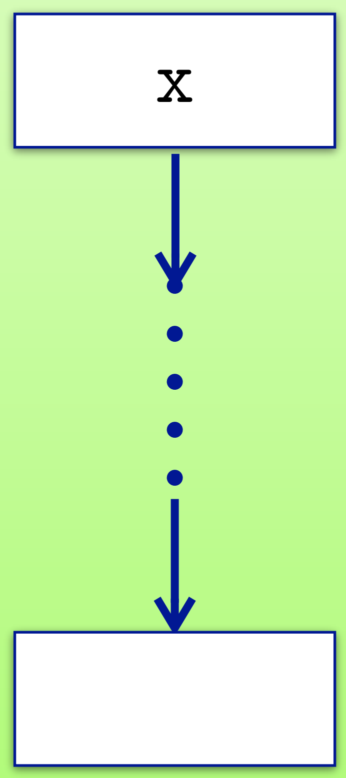
Is there a program execution where at some time variable



of type T ?

Example

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

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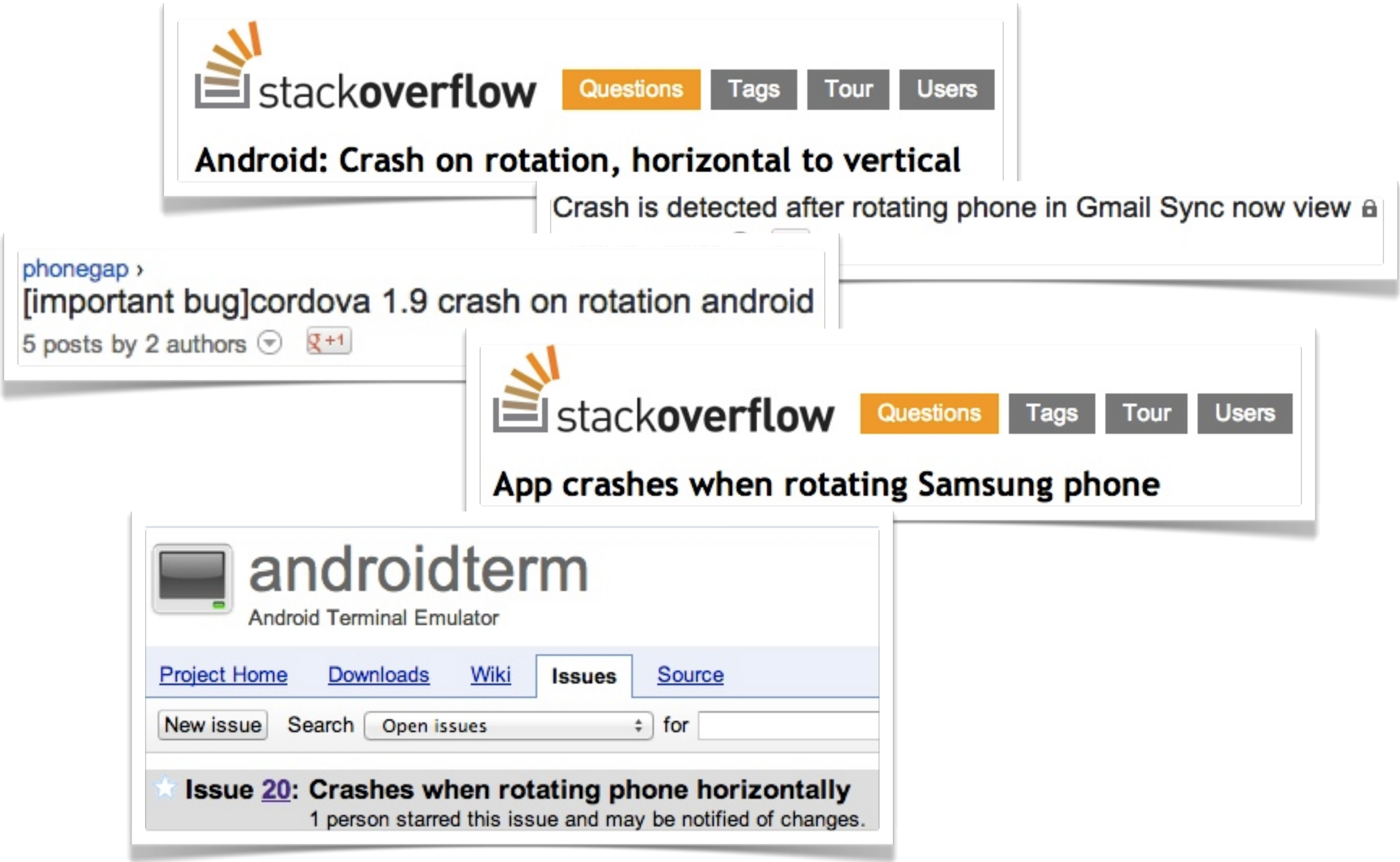

How is this useful? We identify memory leaks that cause your app to crash!

Android memory leaks underly rotation-based crashes.

`Activity` objects encapsulate the UI

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`Activity` objects encapsulate the UI

Android OS

of type `Activity`

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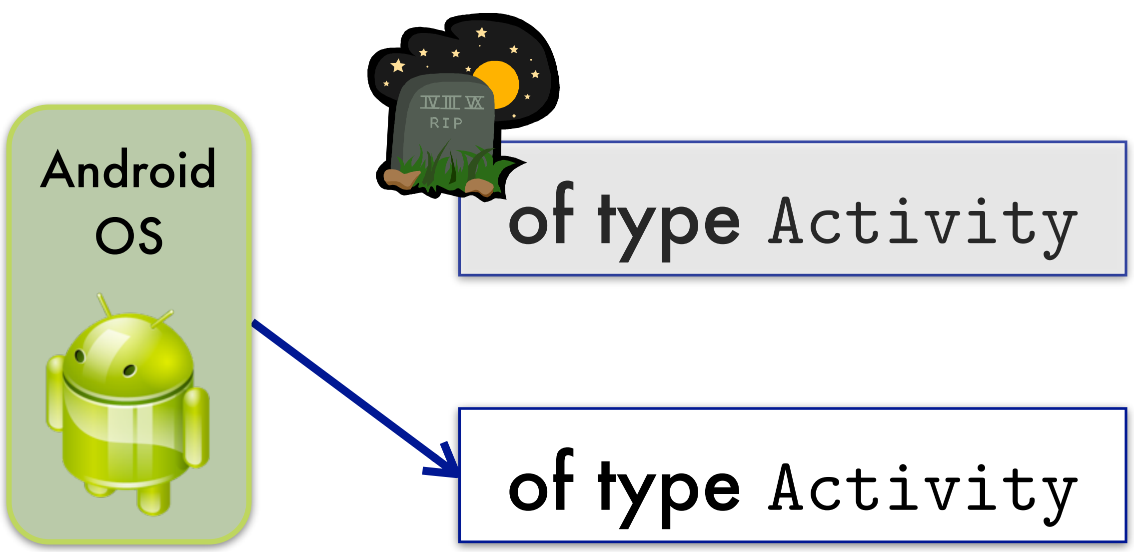

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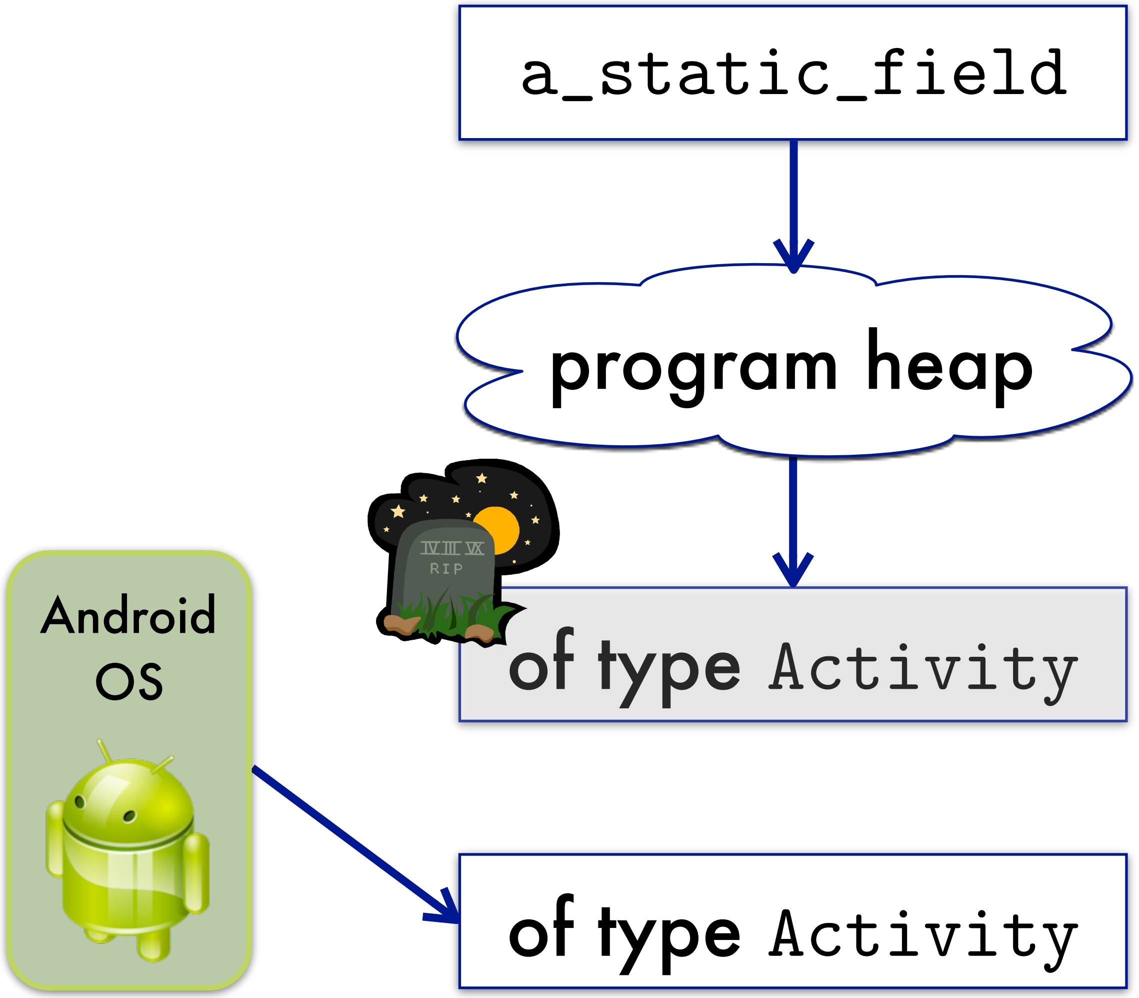

`Activity` objects encapsulate the UI

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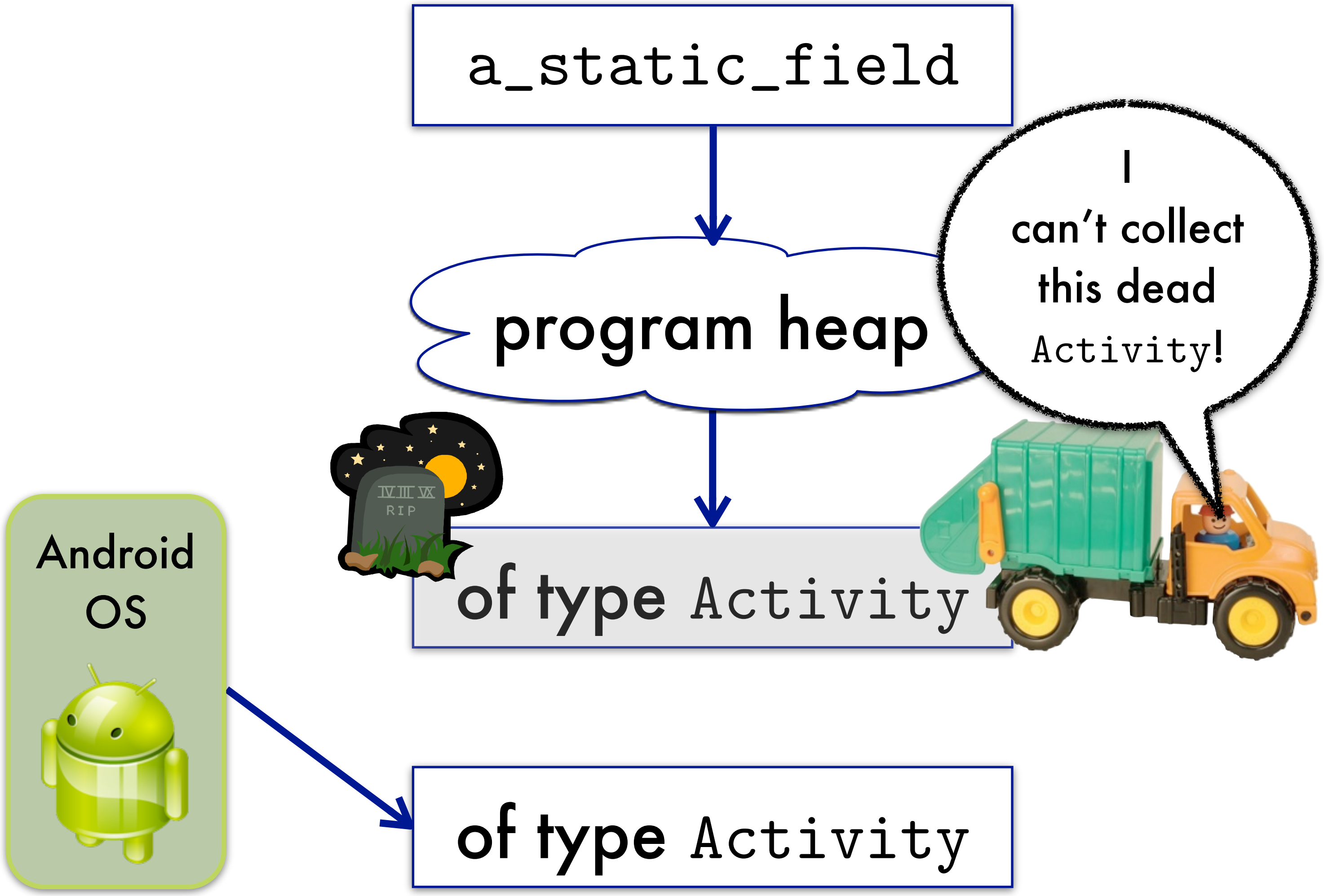

Activity objects encapsulate the UI

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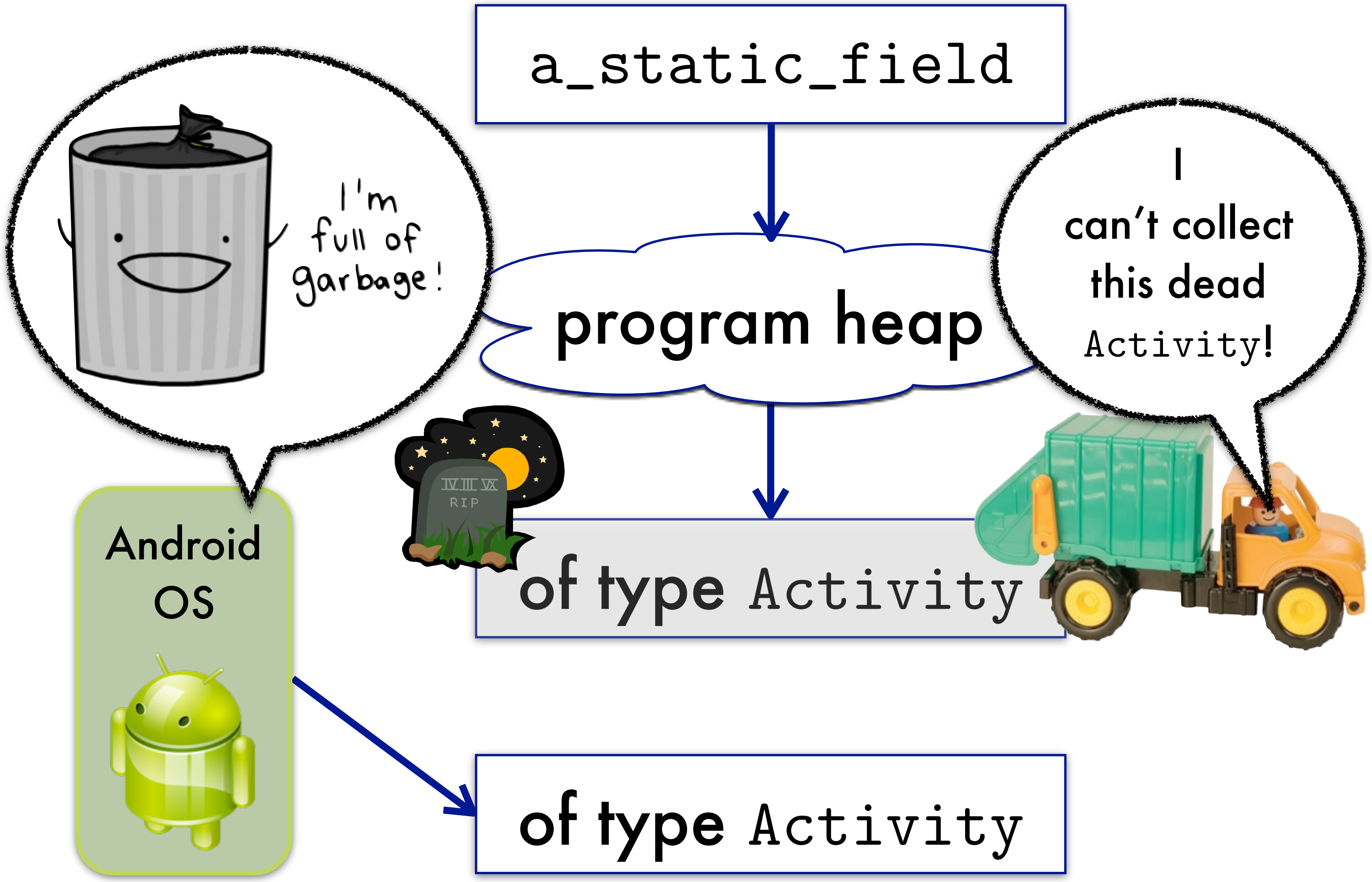

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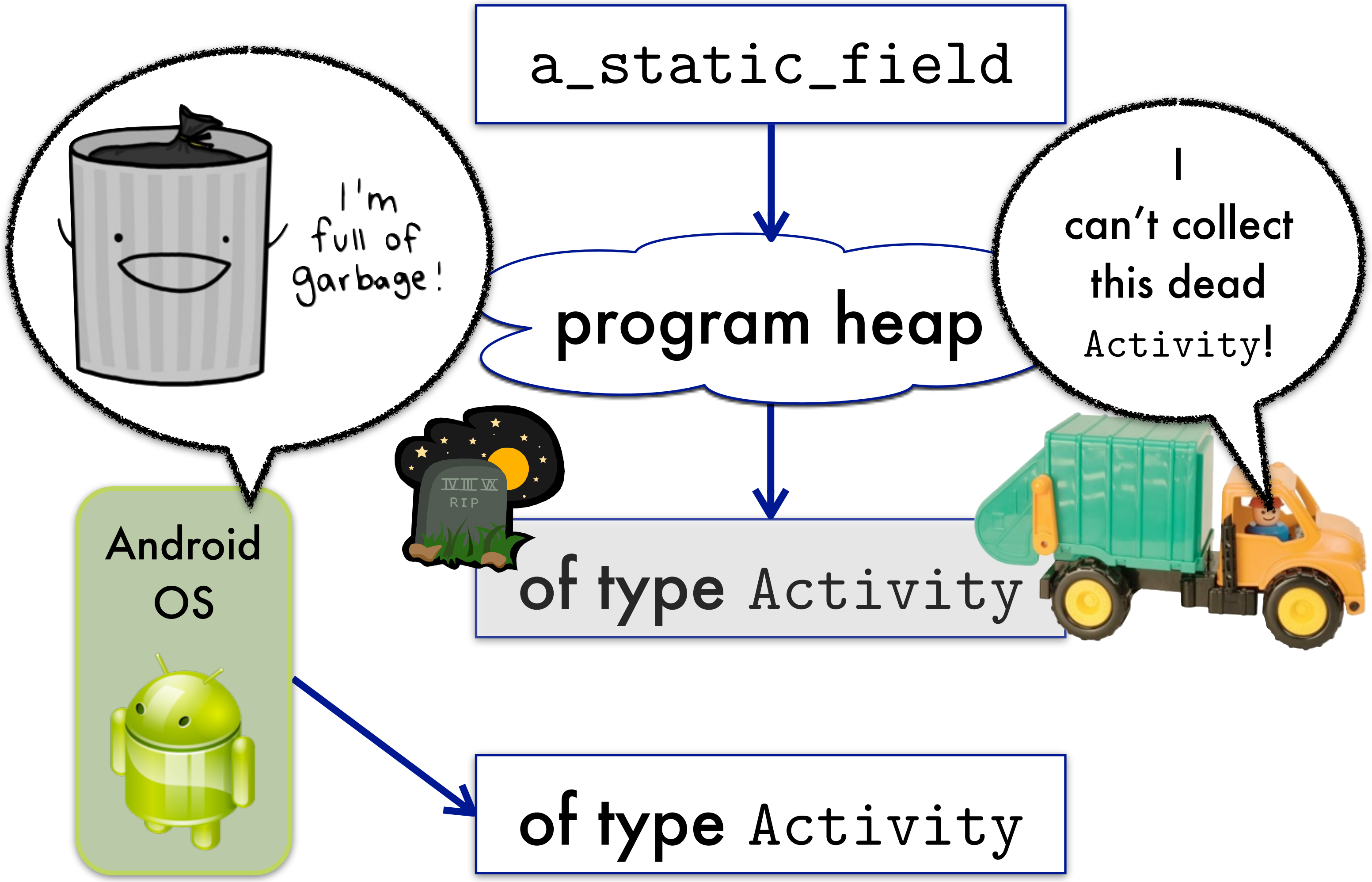
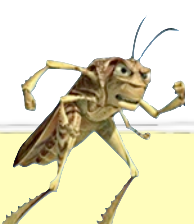


Activity **objects encapsulate the UI**



Bug: Holding reference to "old" Activity

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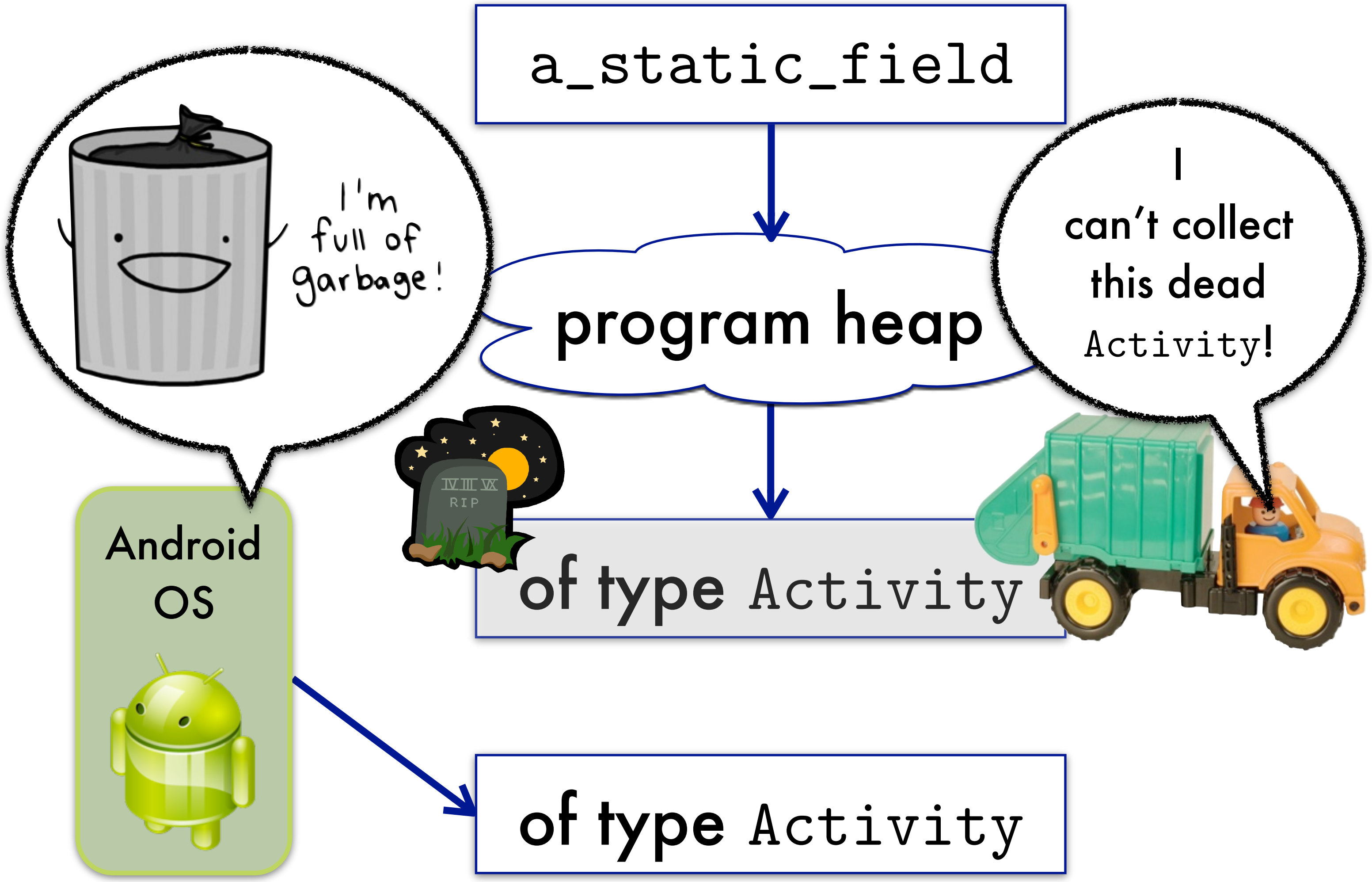
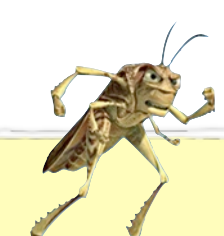


Activity objects encapsulate the UI

"an Activity leak"



Bug: Holding reference to "old" Activity

The expert recommendation …

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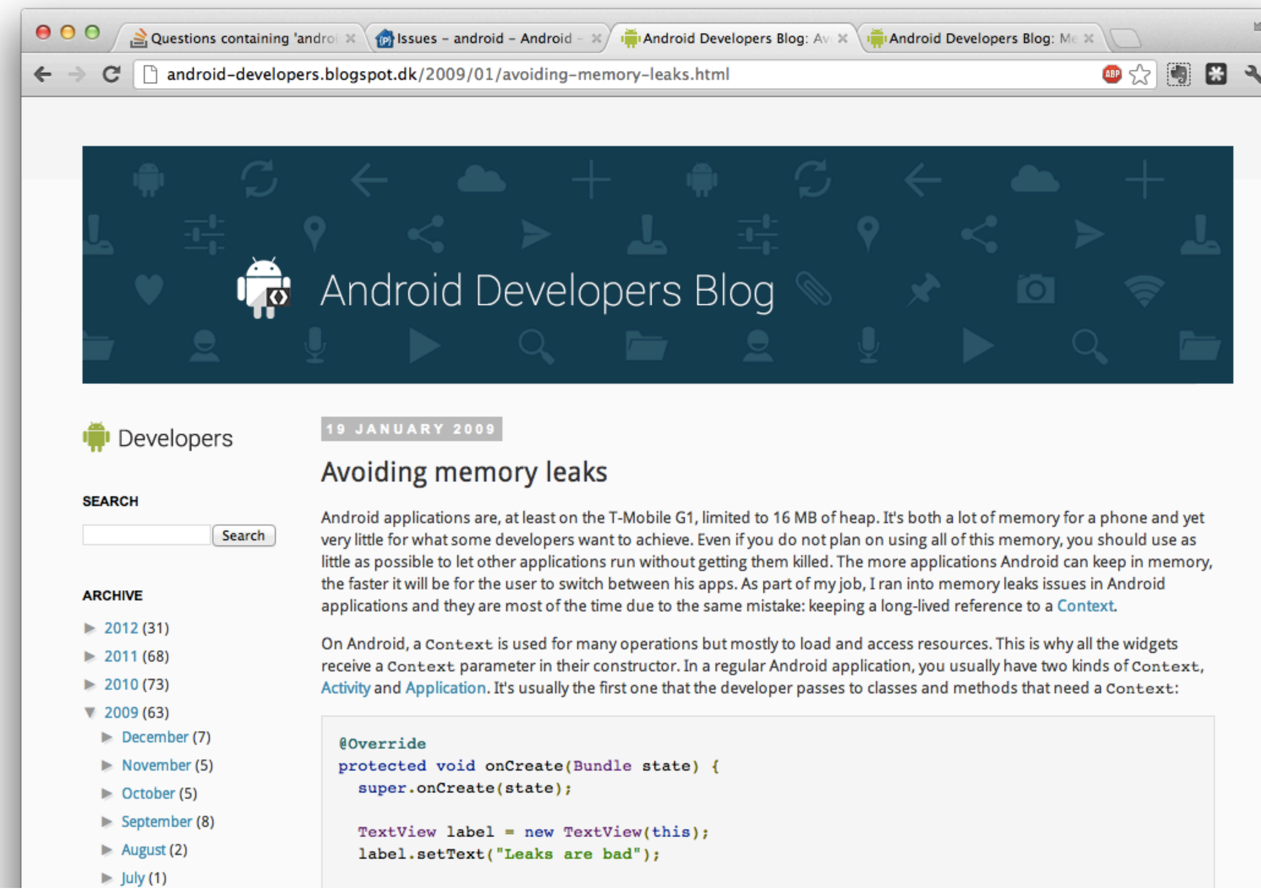
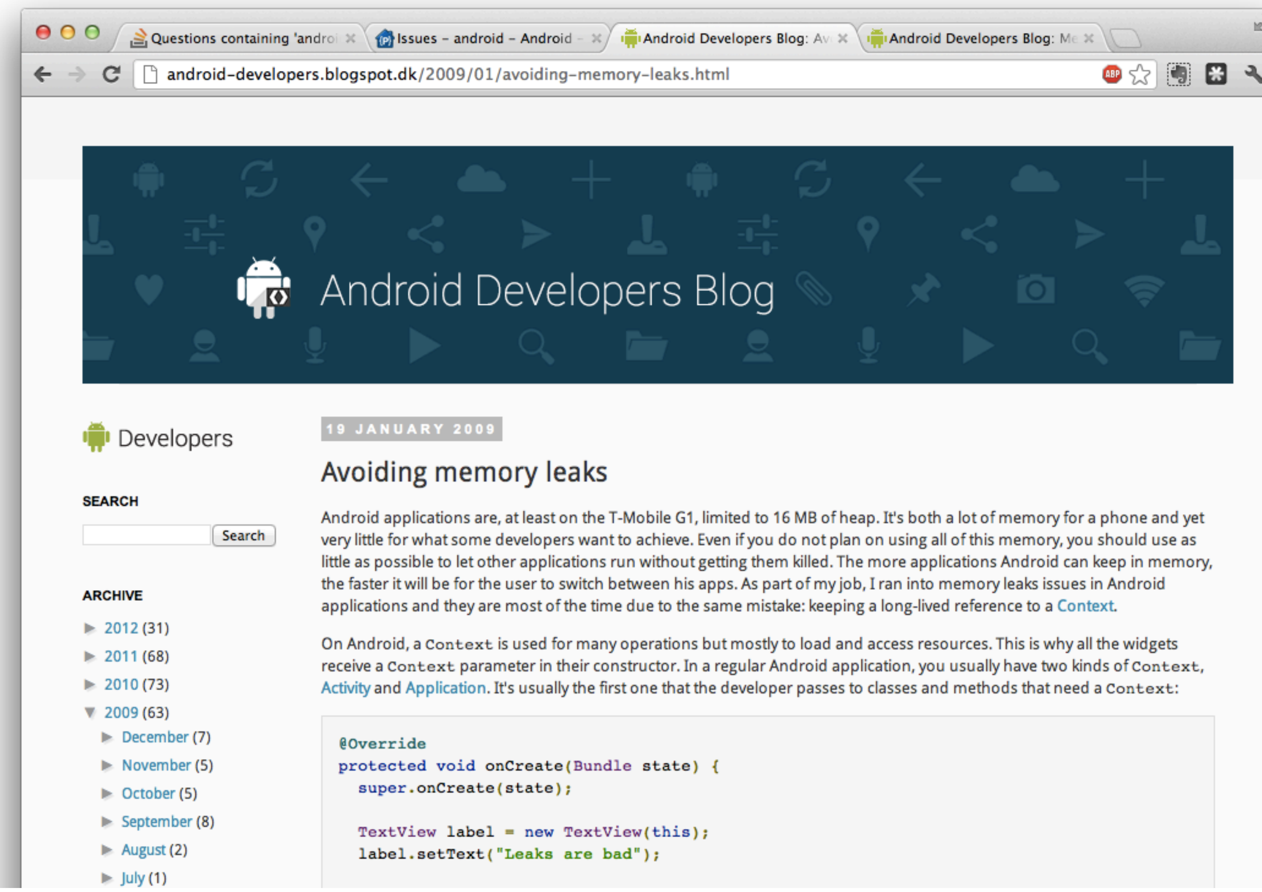


The expert recommendation …

“Do not keep long-lived references to a context-activity”



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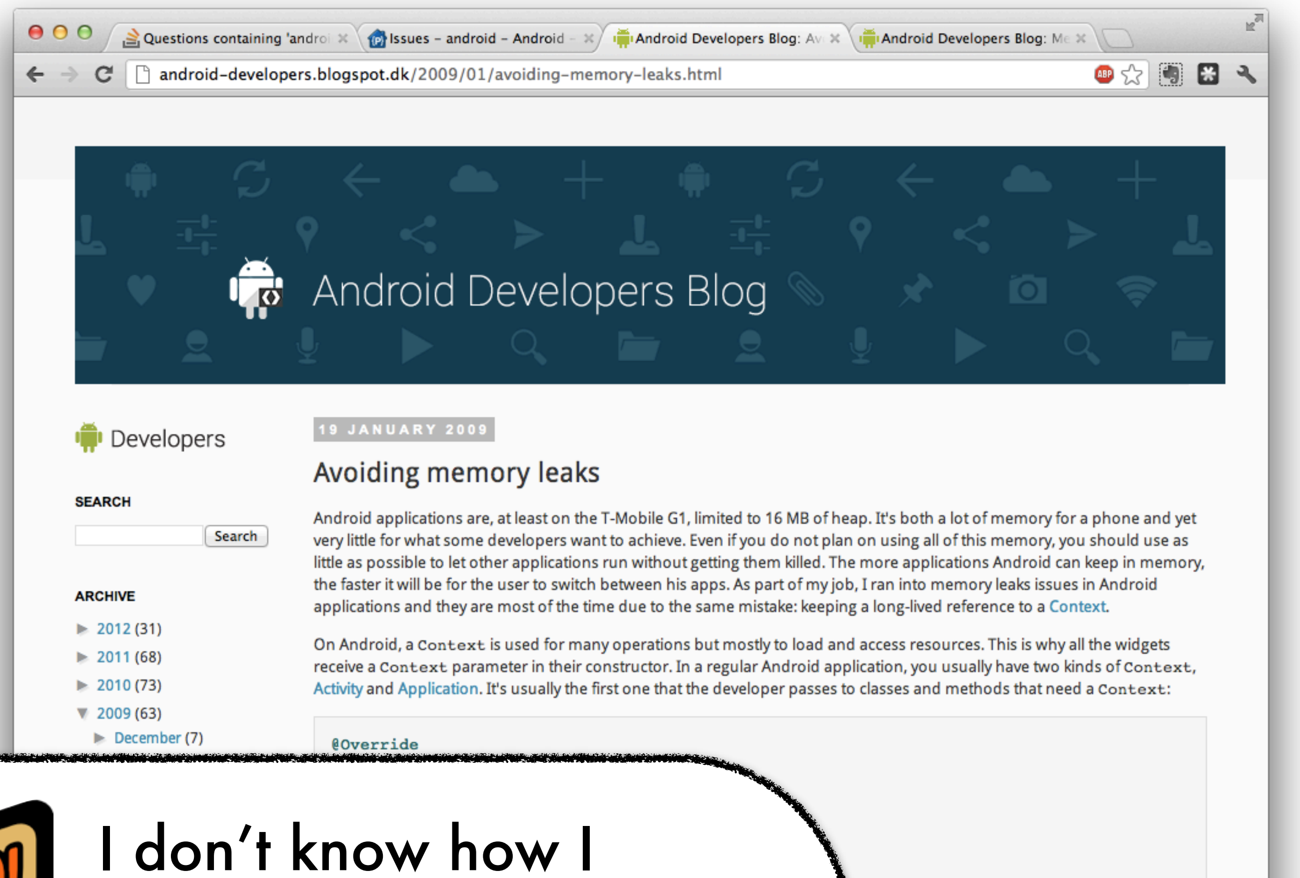
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19 JANUARY 2009

Avoiding memory leaks

Android applications are, at least on the T-Mobile G1, limited to 16 MB of heap. It's both a lot of memory for a phone and yet very little for what some developers want to achieve. Even if you do not plan on using all of this memory, you should use as little as possible to let other applications run without getting them killed. The more applications Android can keep in memory, the faster it will be for the user to switch between his apps. As part of my job, I ran into memory leaks issues in Android applications and they are most of the time due to the same mistake: keeping a long-lived reference to a Context.

On Android, a `Context` is used for many operations but mostly to load and access resources. This is why all the widgets receive a `Context` parameter in their constructor. In a regular Android application, you usually have two kinds of `Context`, Activity and Application. It's usually the first one that the developer passes to classes and methods that need a `Context`:

```
@Override
```

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

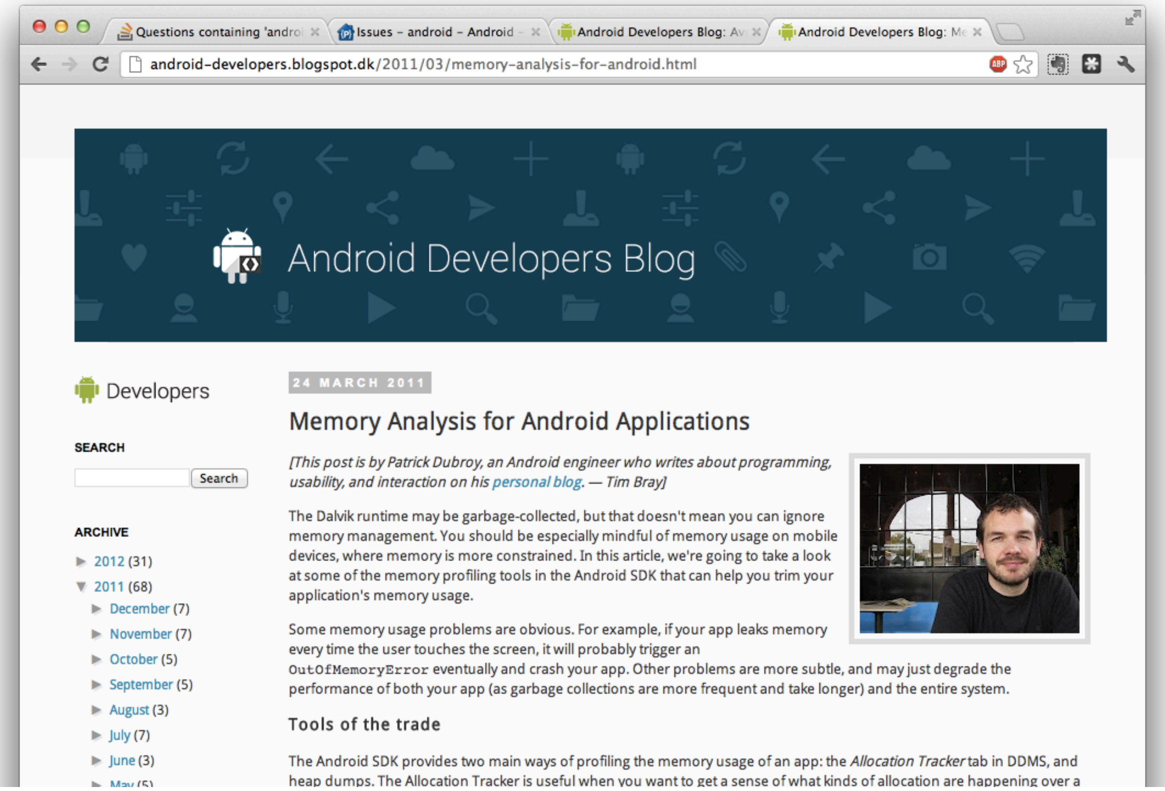
The expert recommendation ...

"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.

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



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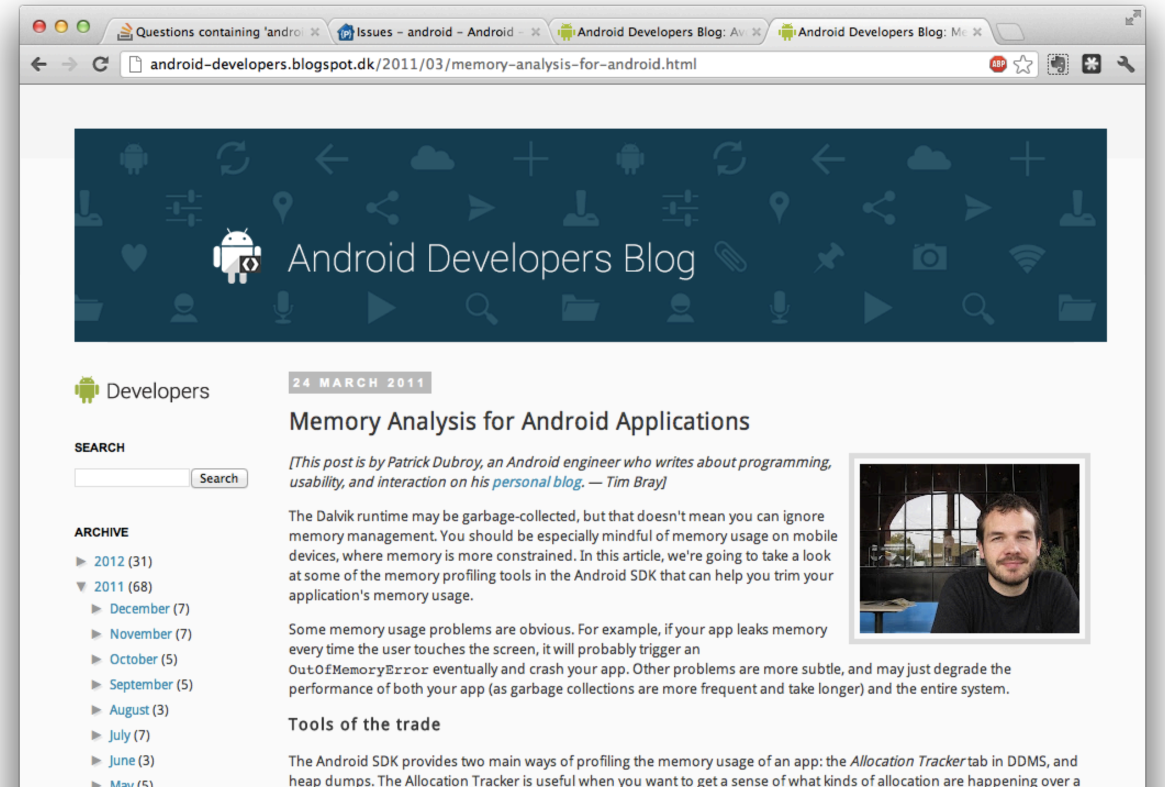
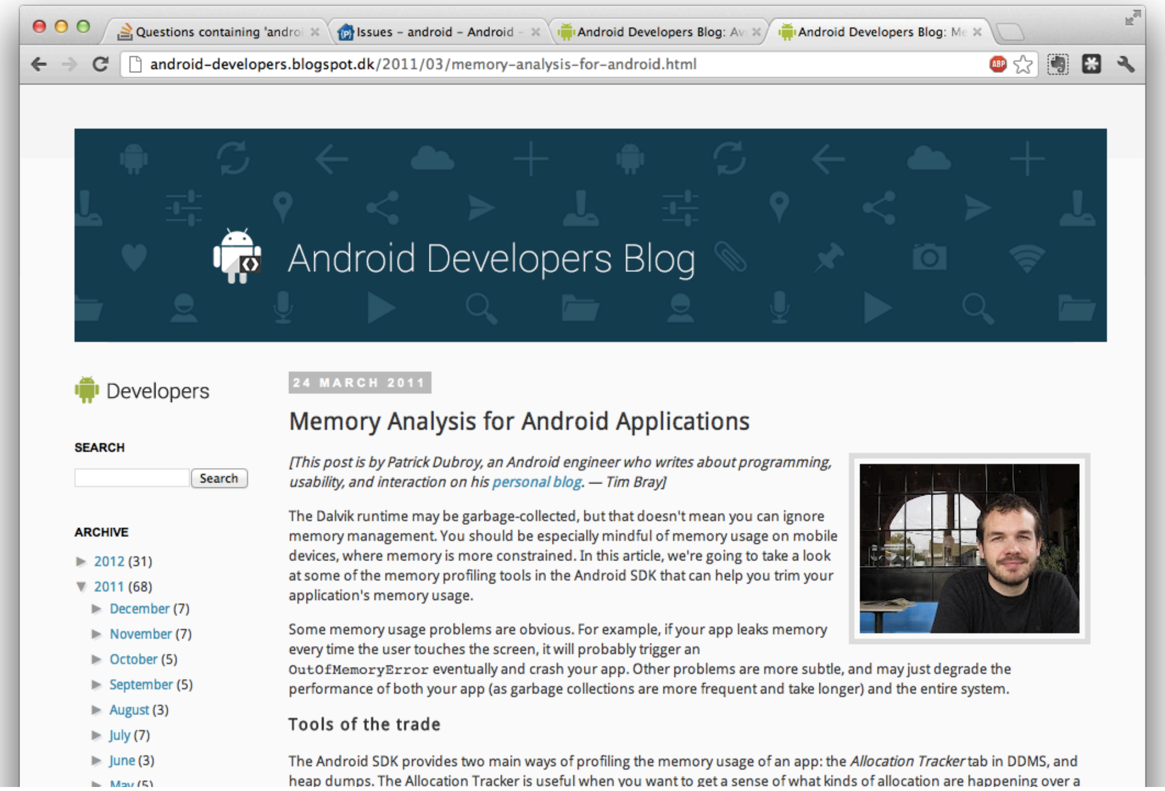
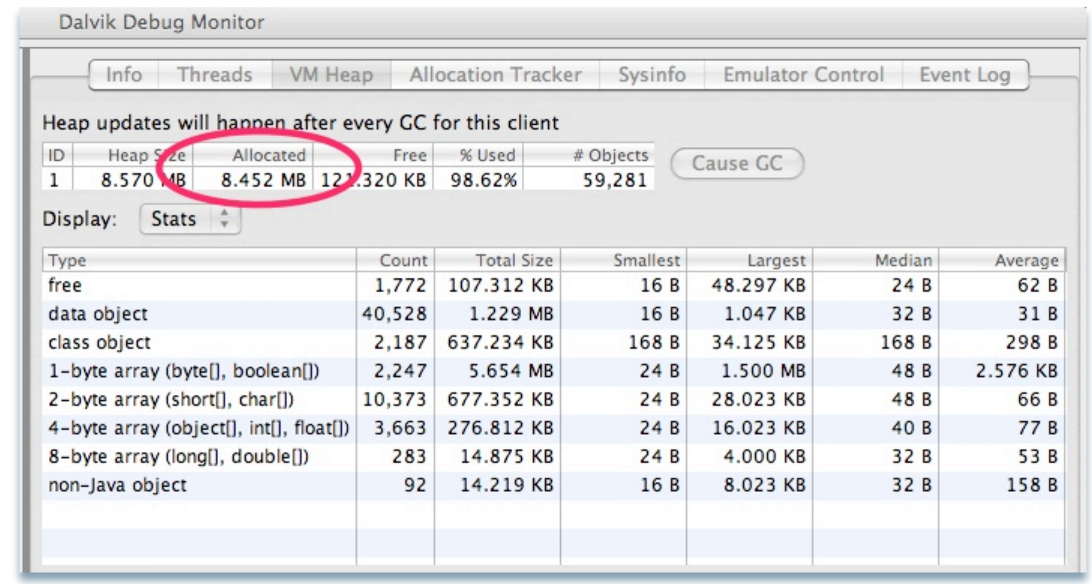


1. Run the app

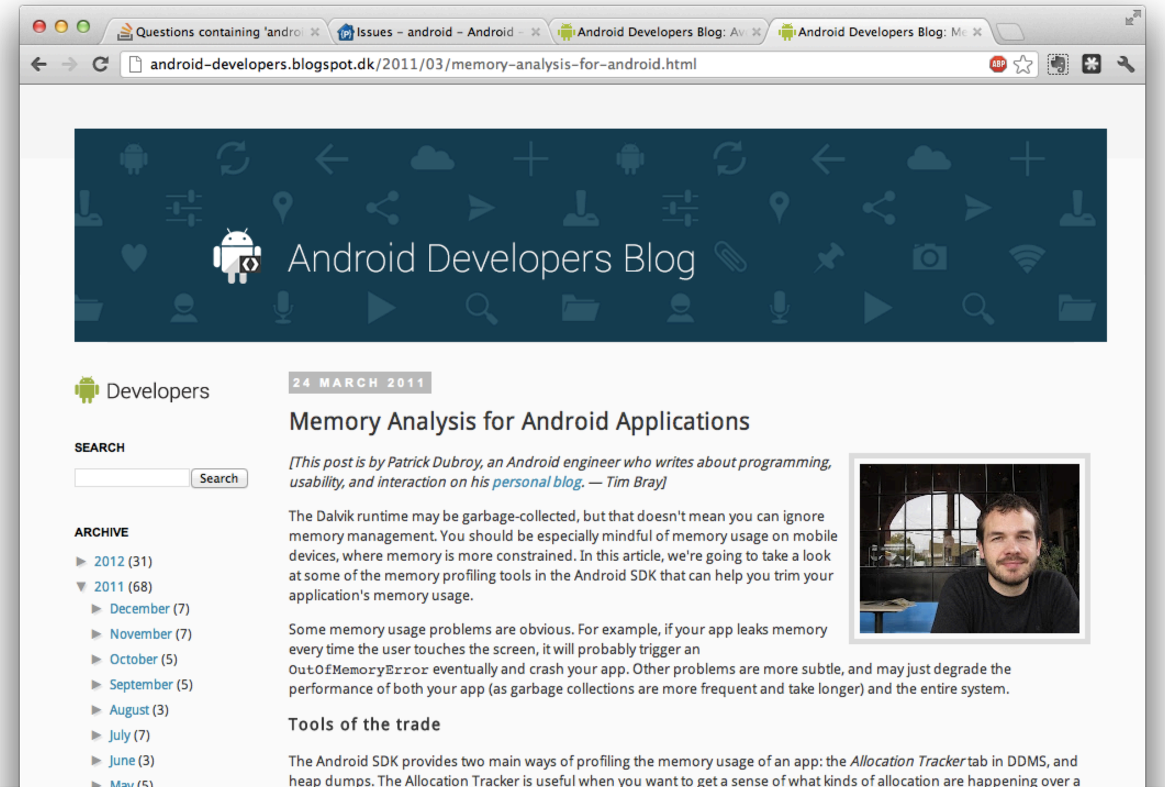
The state of practice in debugging `Activity` leaks …

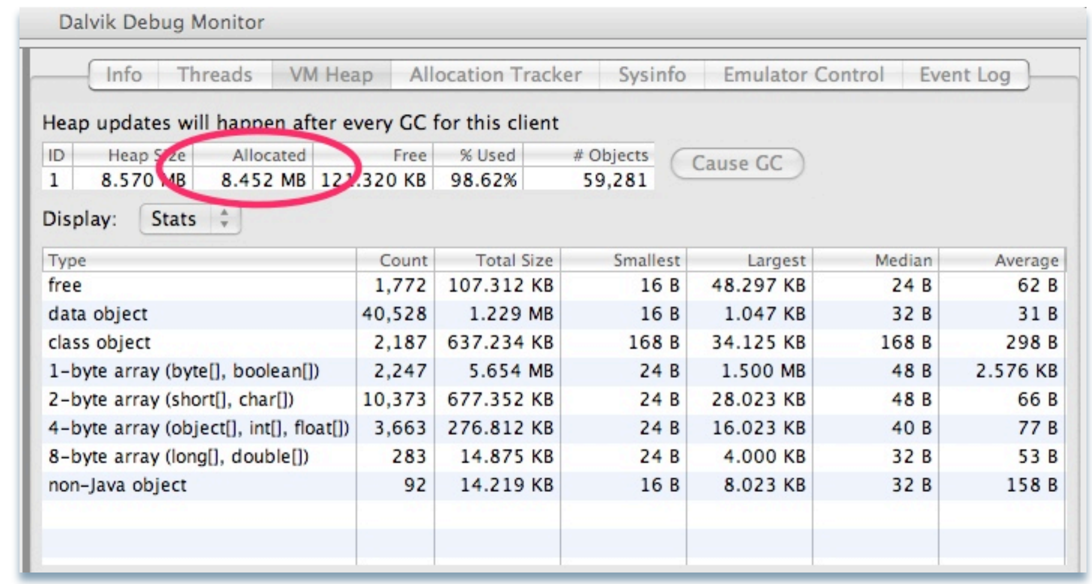


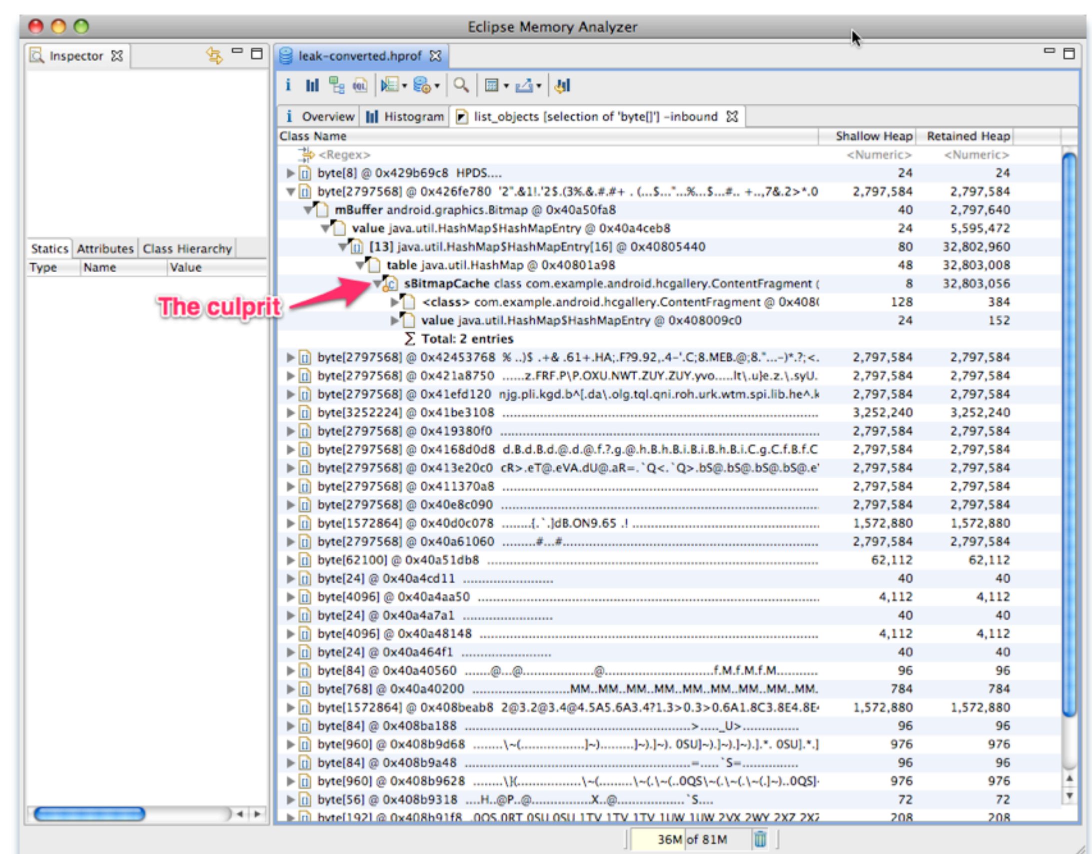


1. Run the app
2. Watch the heap usage

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







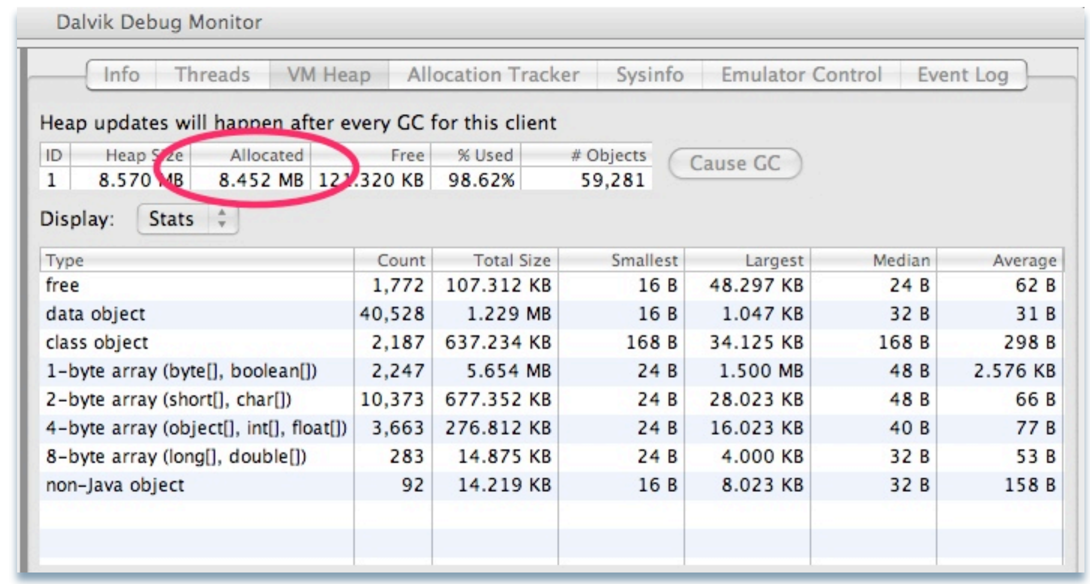
1. Run the app
2. Watch the heap usage
3. Dump the heap. Dig around and **hope** to find the culprit

The state of practice in debugging `Activity` leaks …

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

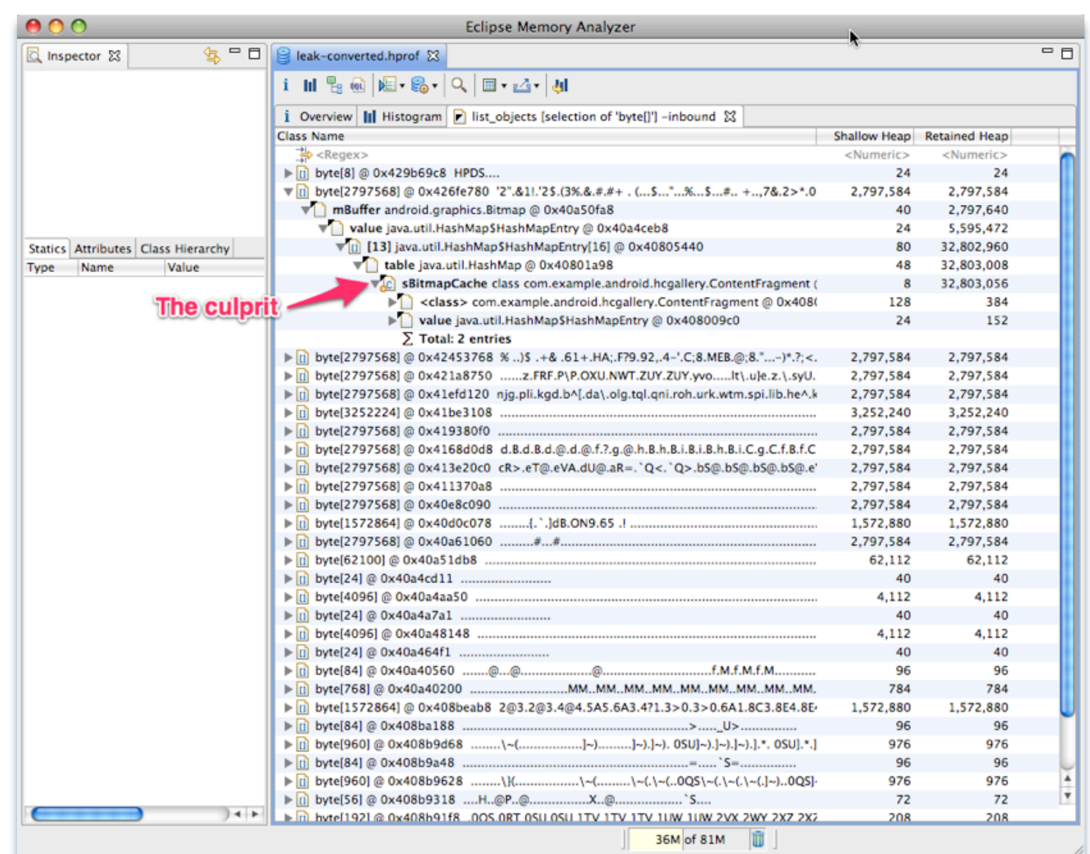
- Where in the code is this object allocated?
- What about the object that references it?
- Where is the reference created?
- Is this reference needed?
- For what periods?

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



ID	Heap Size	Allocated	Free	% Used	# Objects
1	8.570 MB	8.452 MB	12?.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

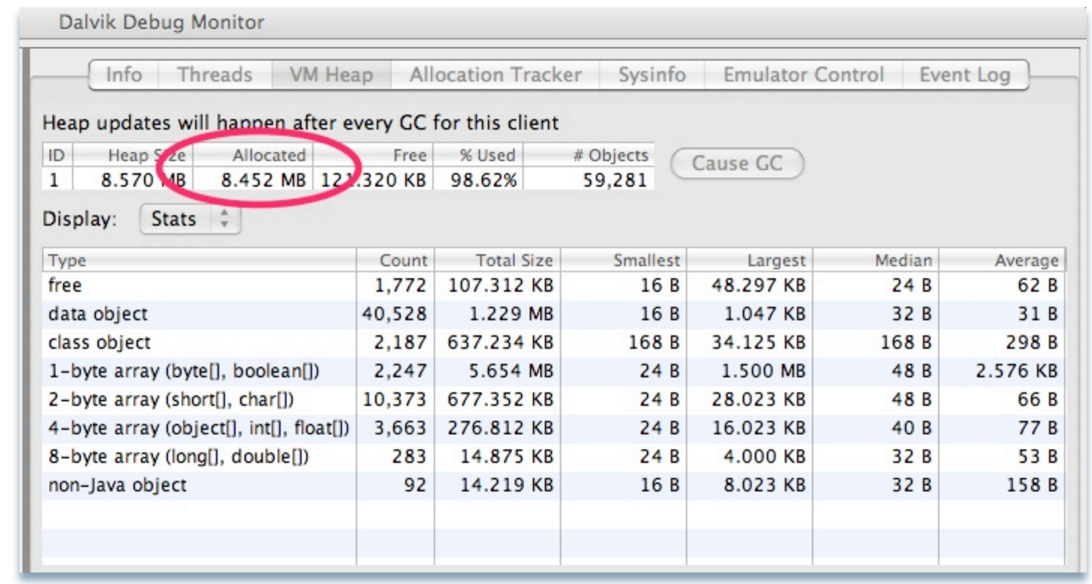


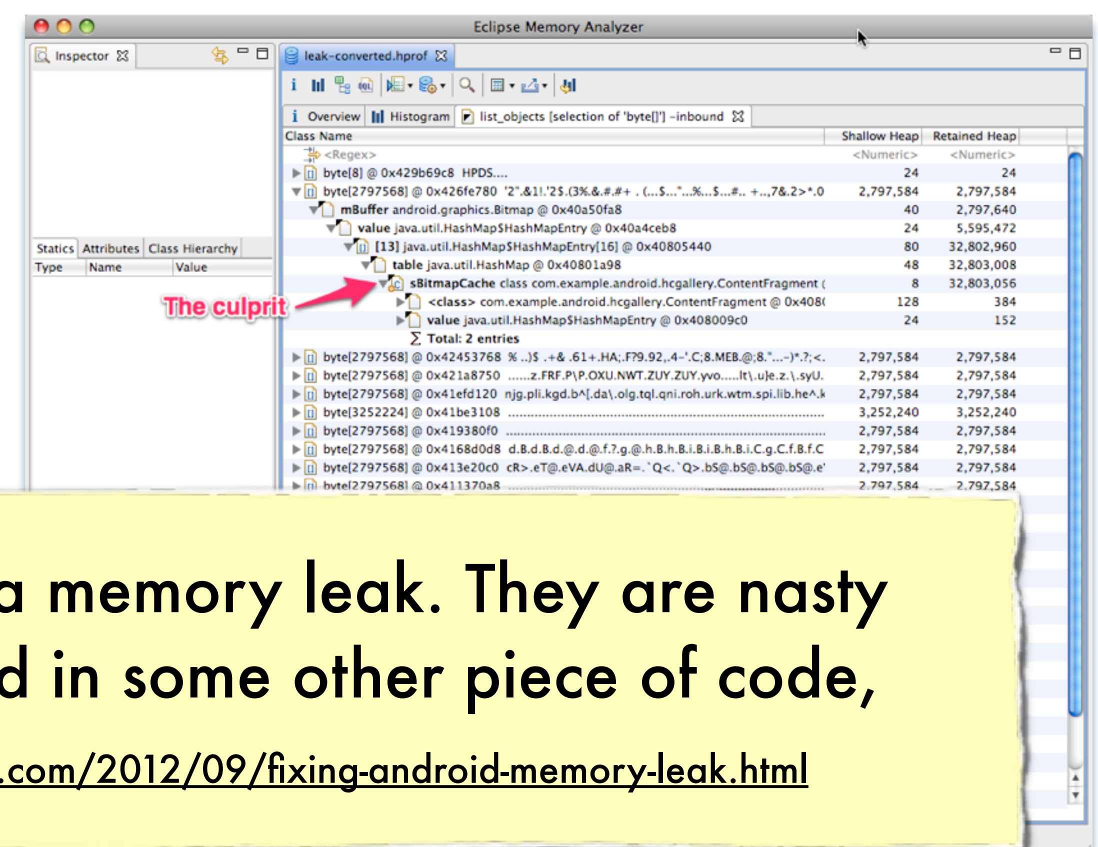
The state of practice in debugging `Activity` leaks …

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 hea Dig





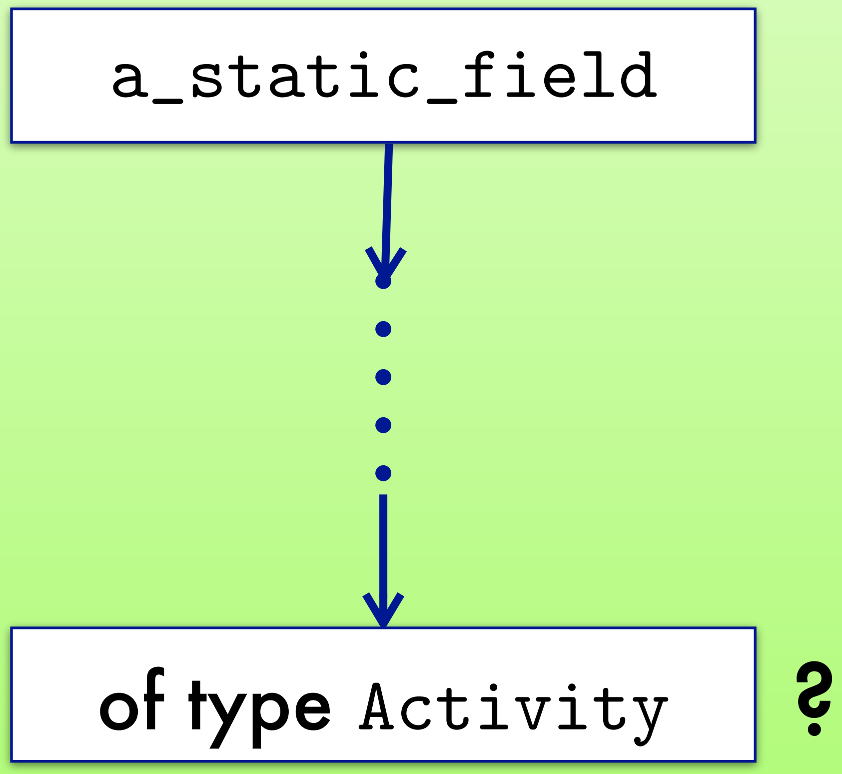
"One of the most dreaded bugs in Android is a memory leak. They are nasty because one piece of code causes an issue and in some other piece of code, your application crashes." – http://therockncoder.blogspot.com/2012/09/fixing-android-memory-leak.html


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 …

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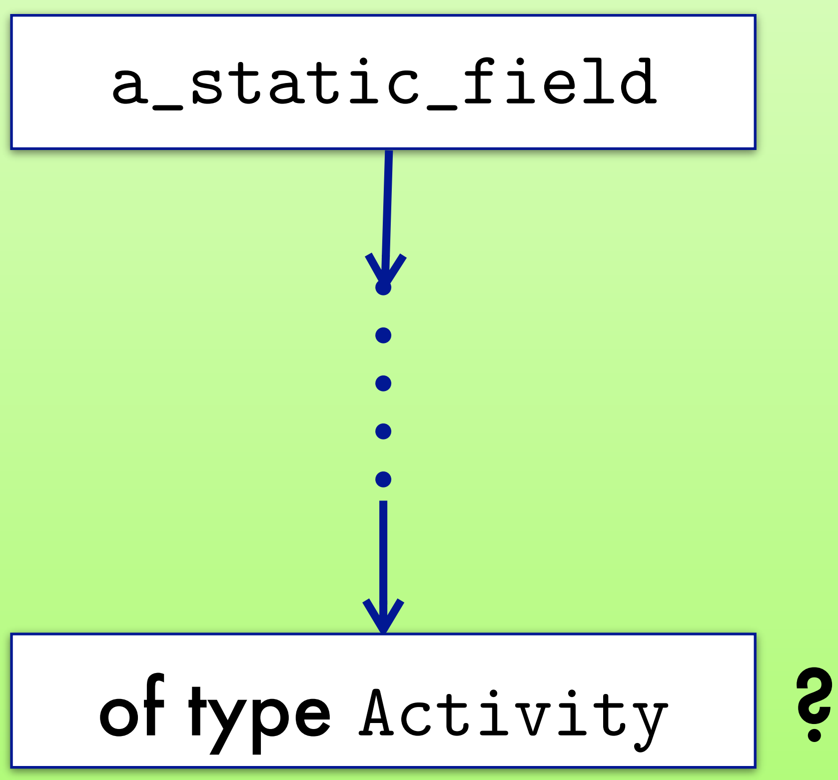


Example

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?

Is there a program execution where at some time

`a_static_field`

⋮

of type `Activity` ?

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

`a_static_field`

⋮

of type `Activity` ?

Example

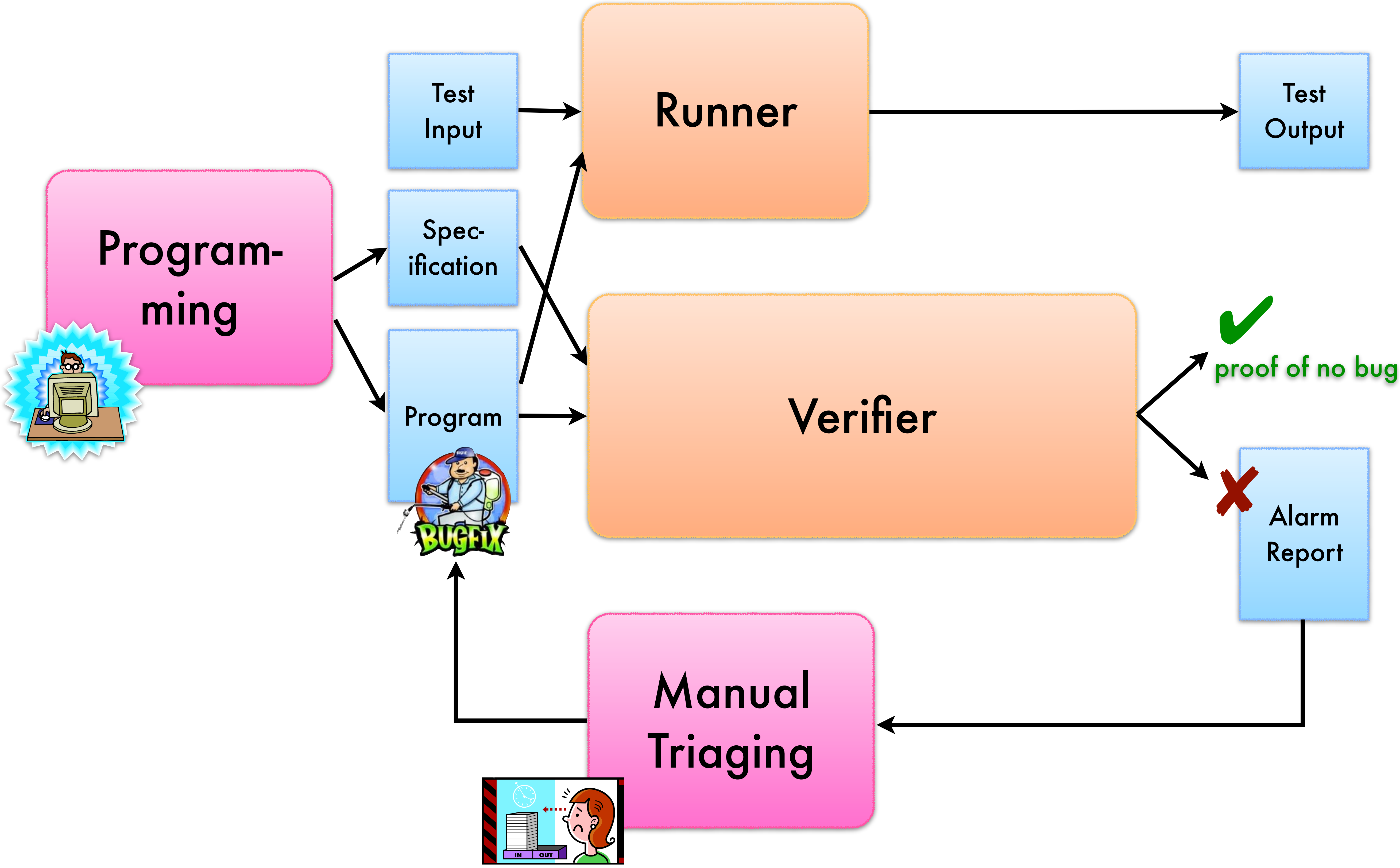
Can be answered with a points-to analysis

with **approximation**

Hidden Truth

Some pointer relations **may** be false

But with the cooperative approach ...



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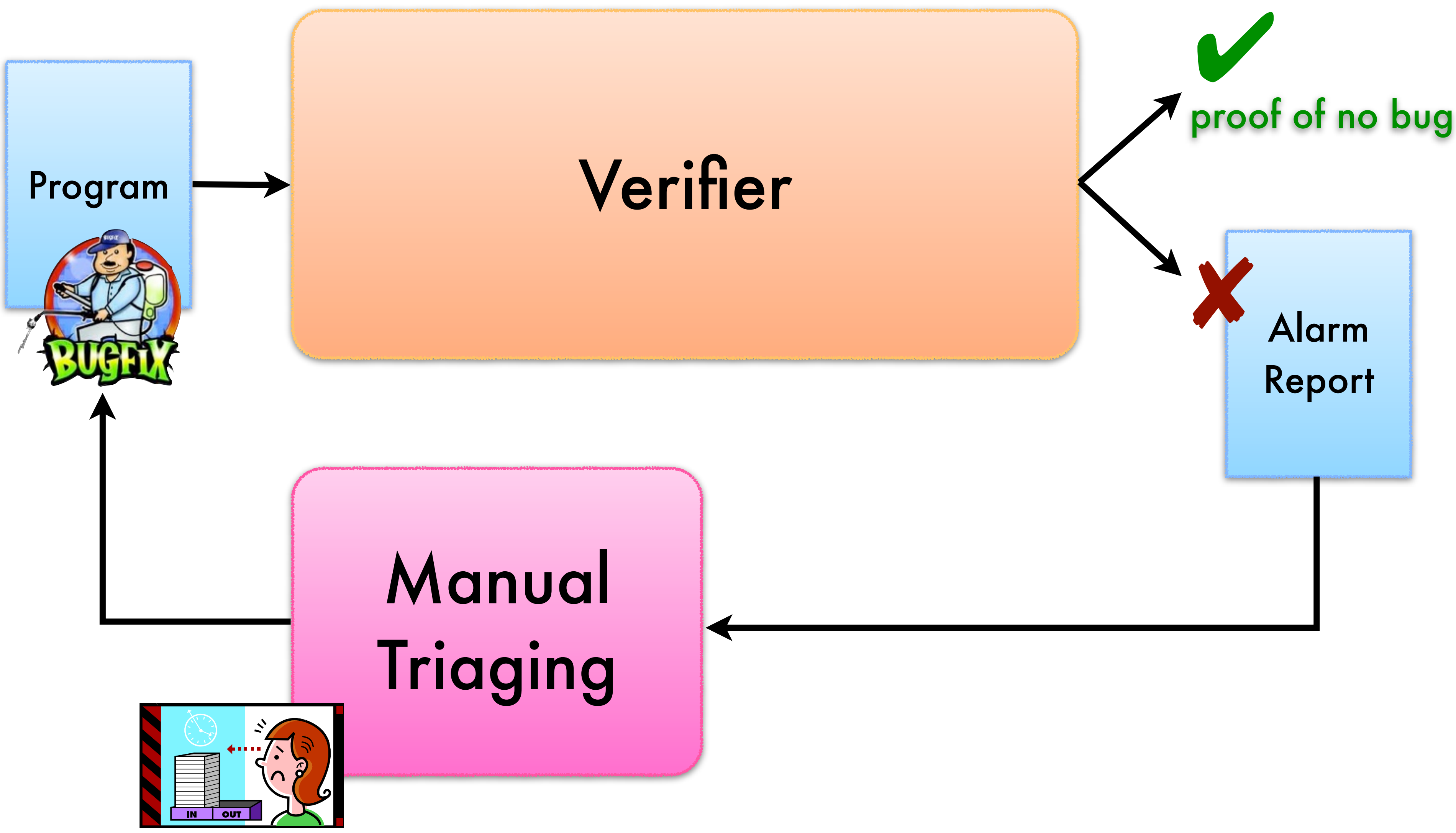
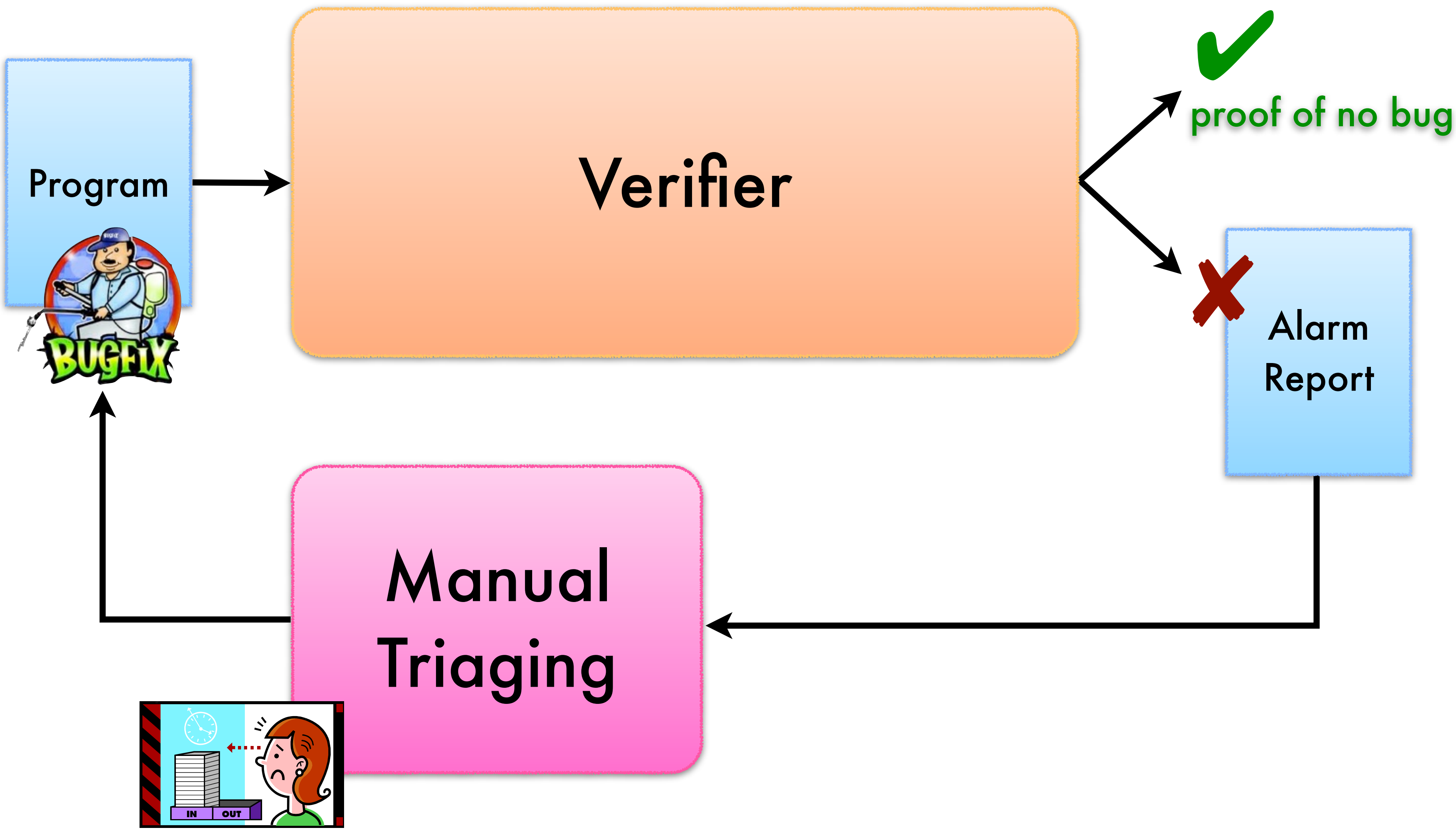


Thresher addresses alarm **triage** in a particularly challenging domain.



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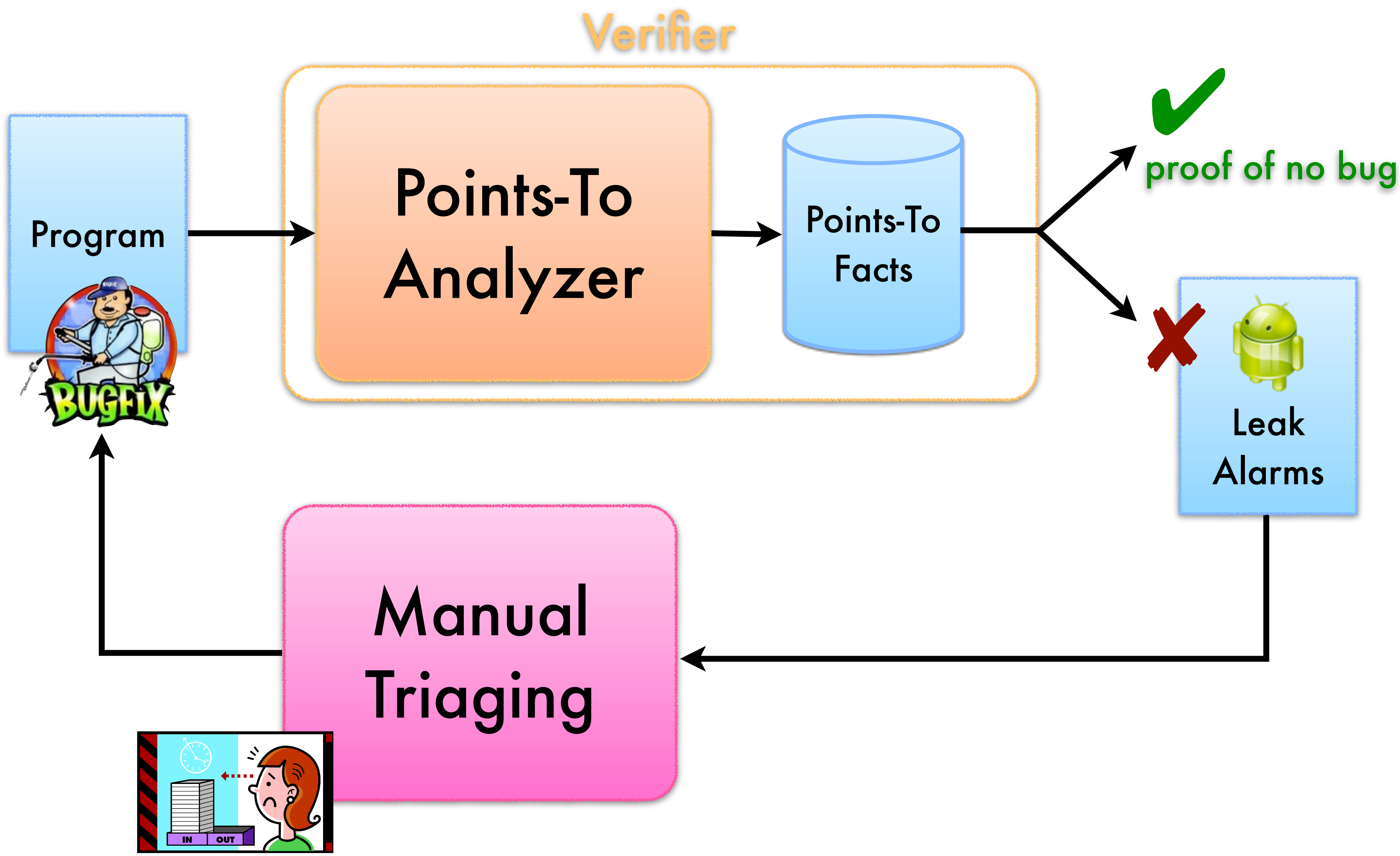

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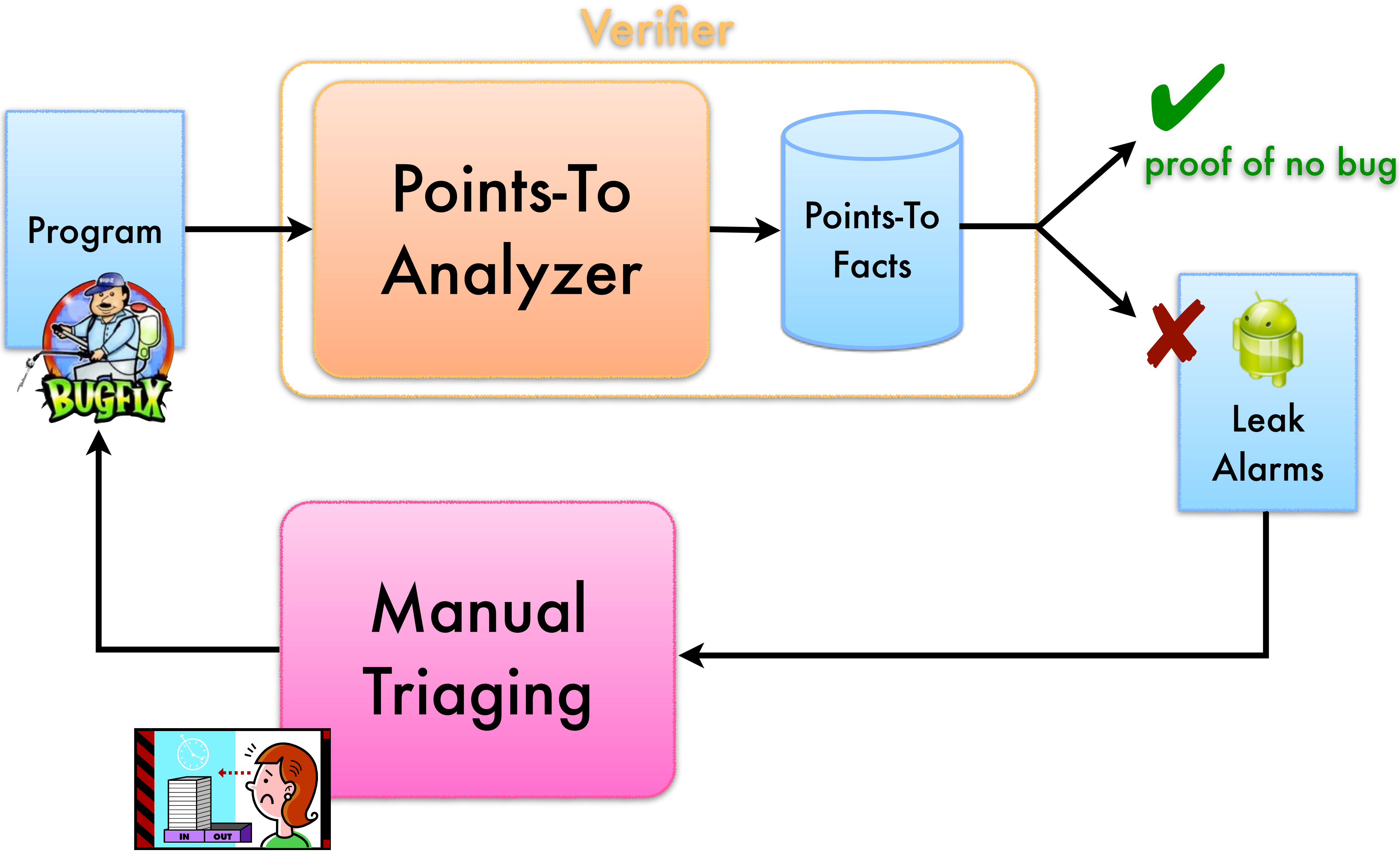

Known: Precise points-to analysis challenging

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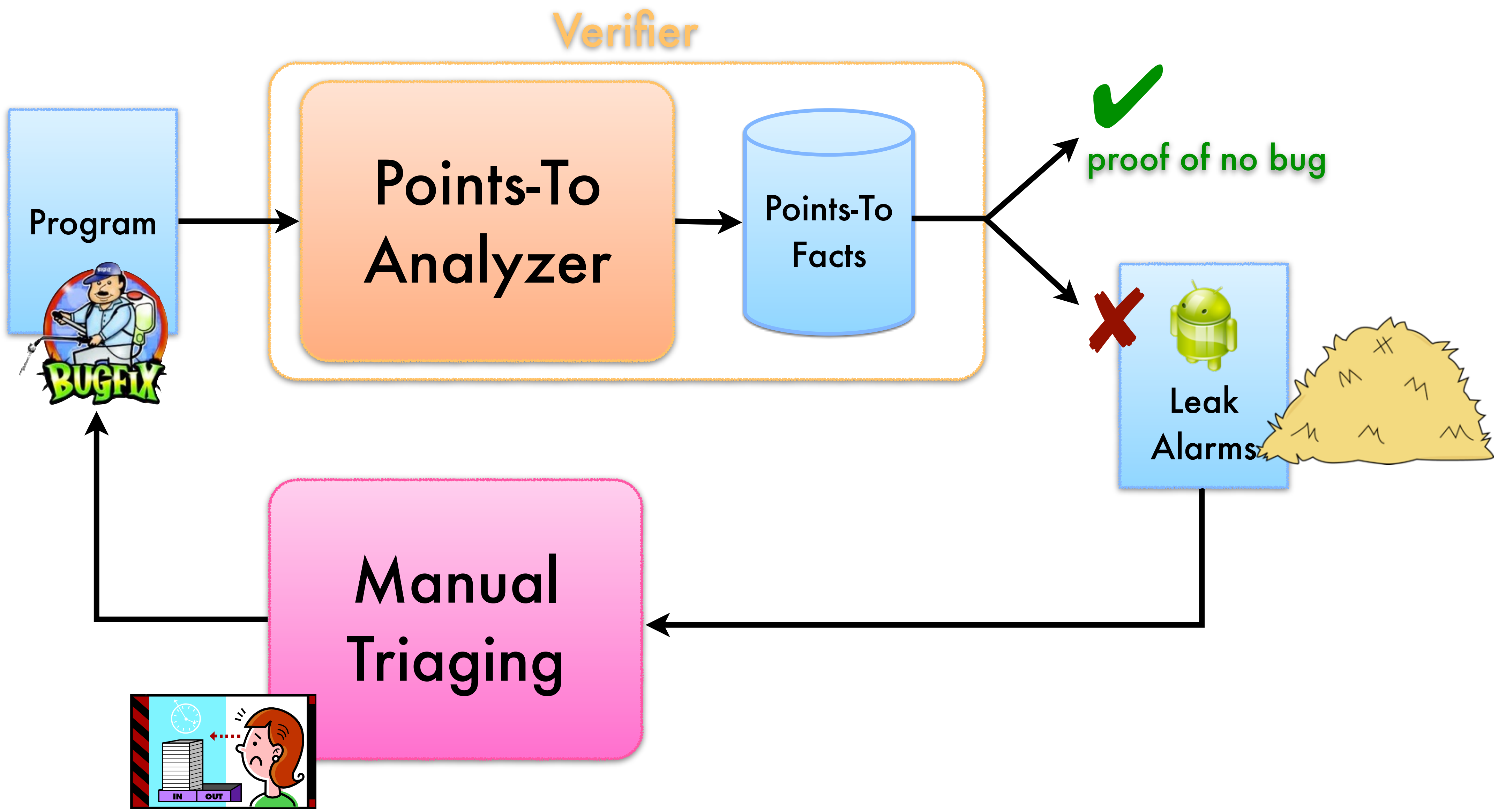

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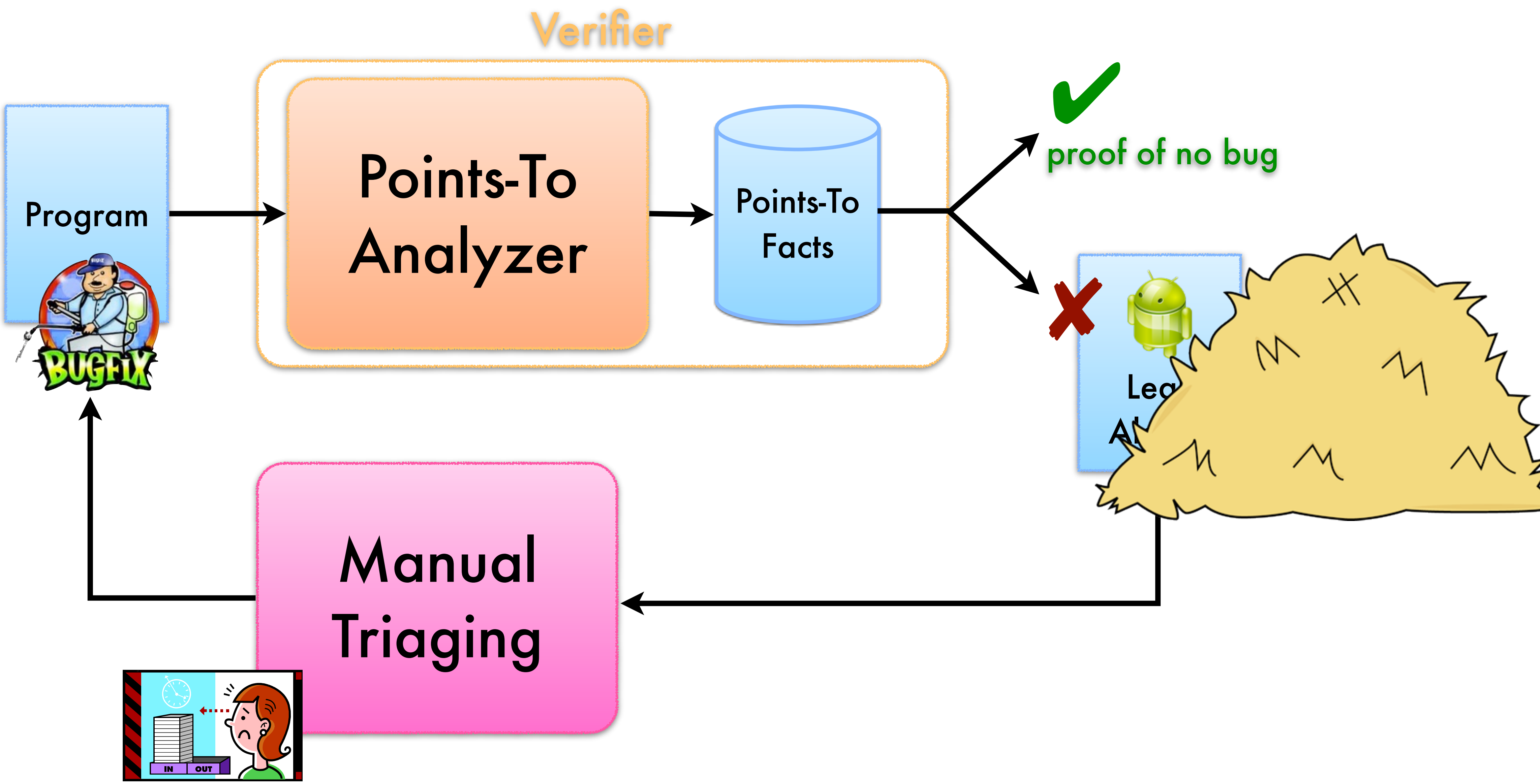

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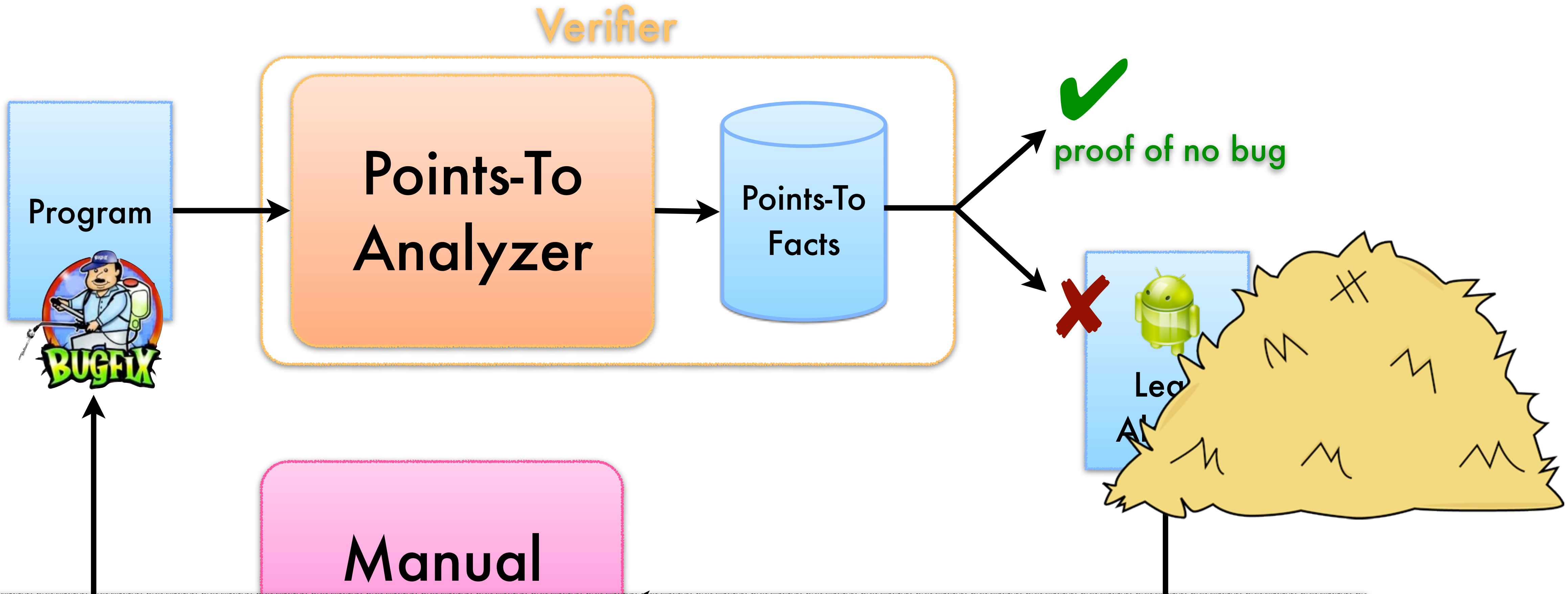

Hind. "Pointer Analysis: Haven't We Solved This Problem Yet?"

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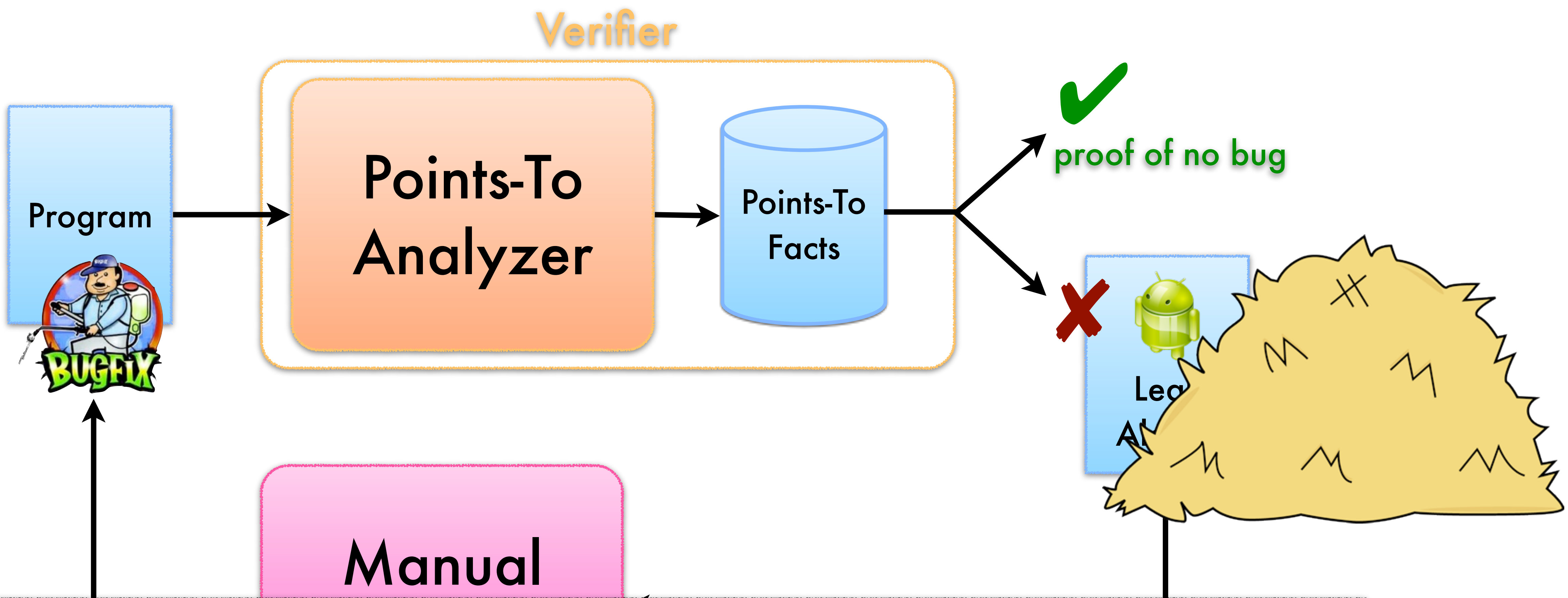

Hind. "Pointer Analysis: Haven't We Solved This Problem Yet?"

- 75 papers, 9 PhD theses

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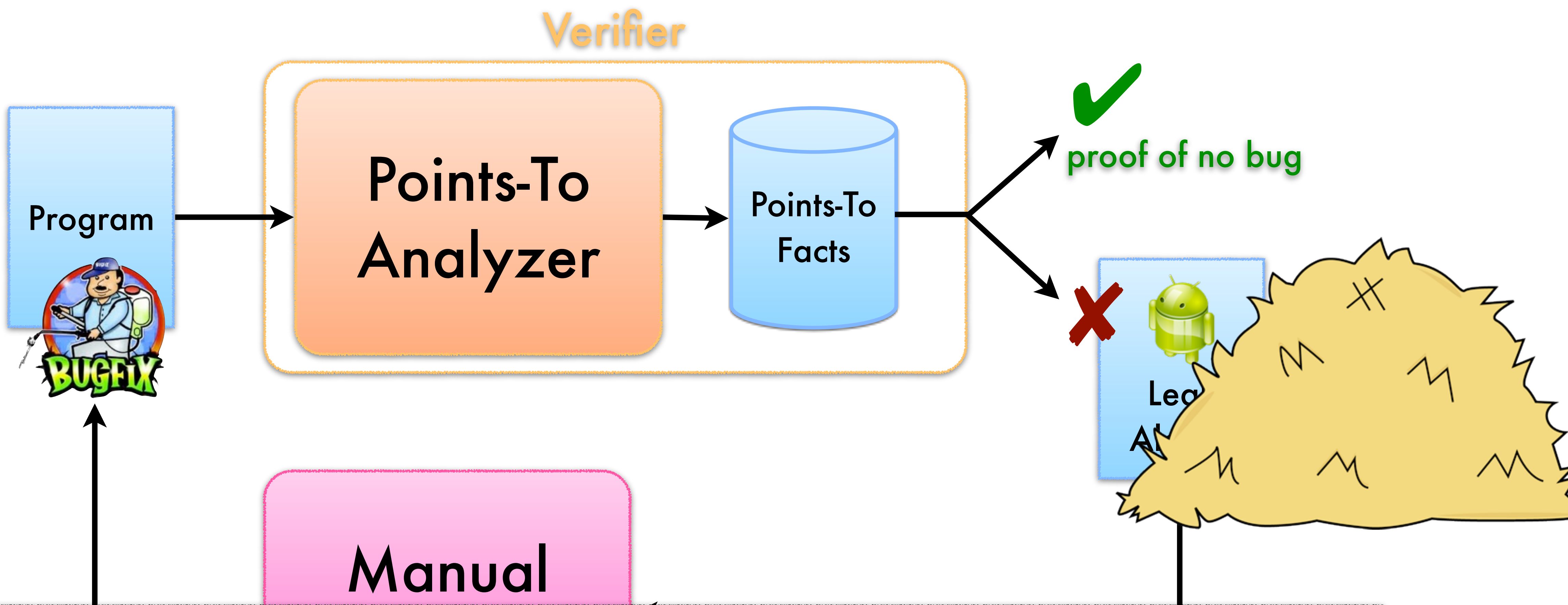

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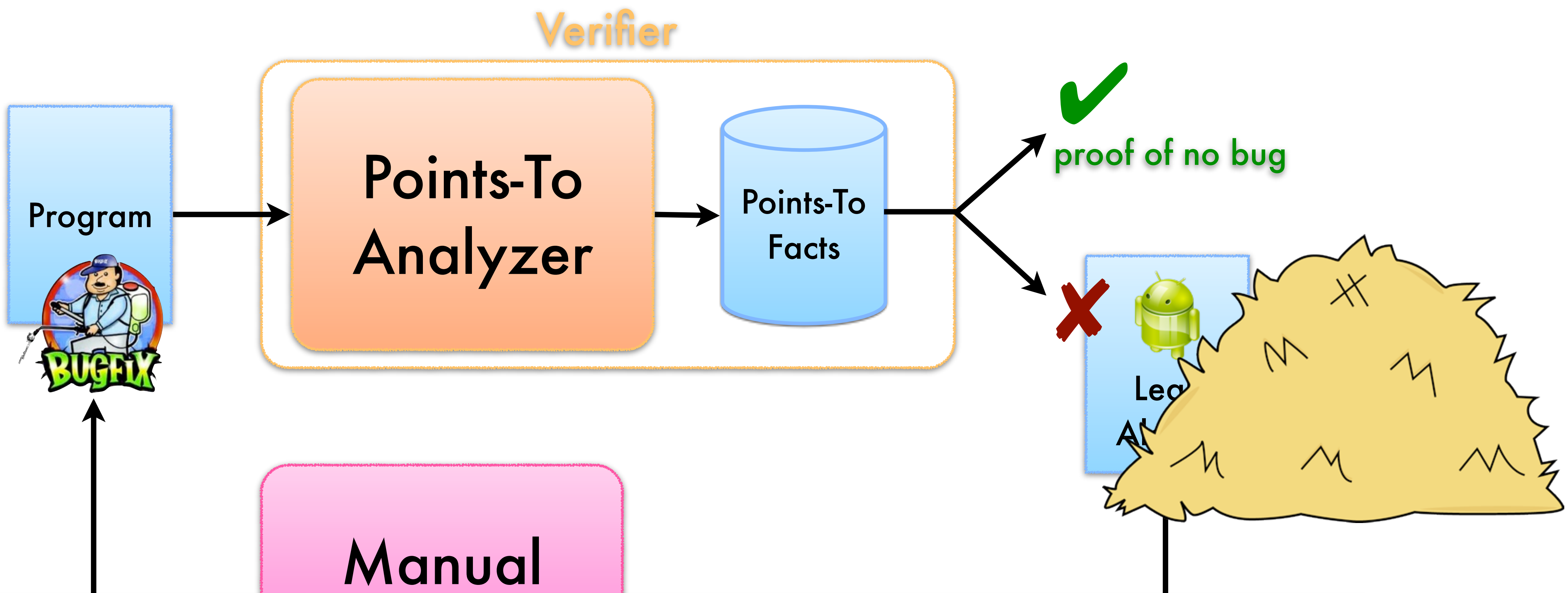

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Dagstuhl 13162: Pointer Analysis (2013)

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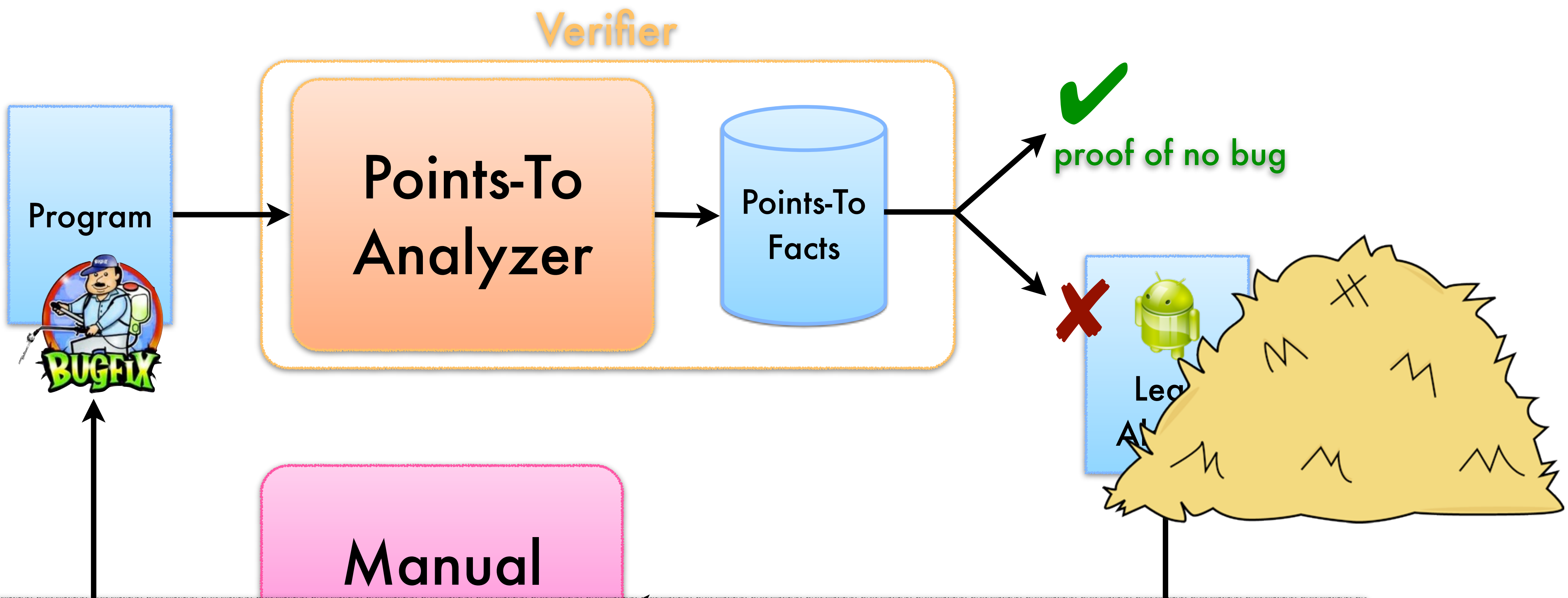

Hind. "Pointer Analysis: Haven't We Solved This Problem Yet?" (2001)

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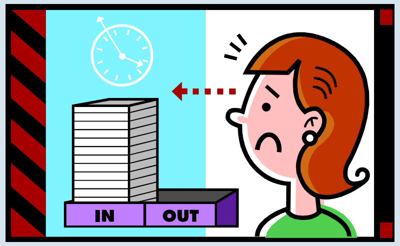
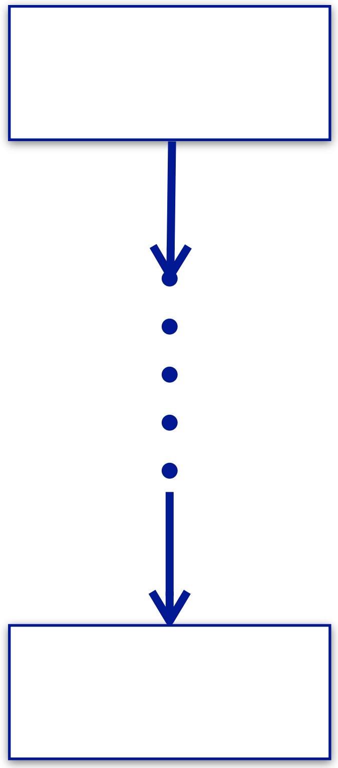
Dagstuhl 13162: Pointer Analysis (2013)

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

Manual triage is particularly hard for heap reachability reports.





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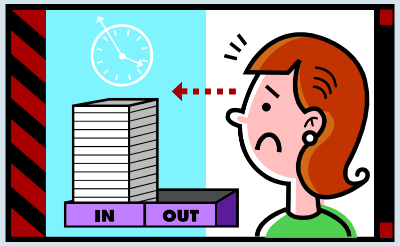
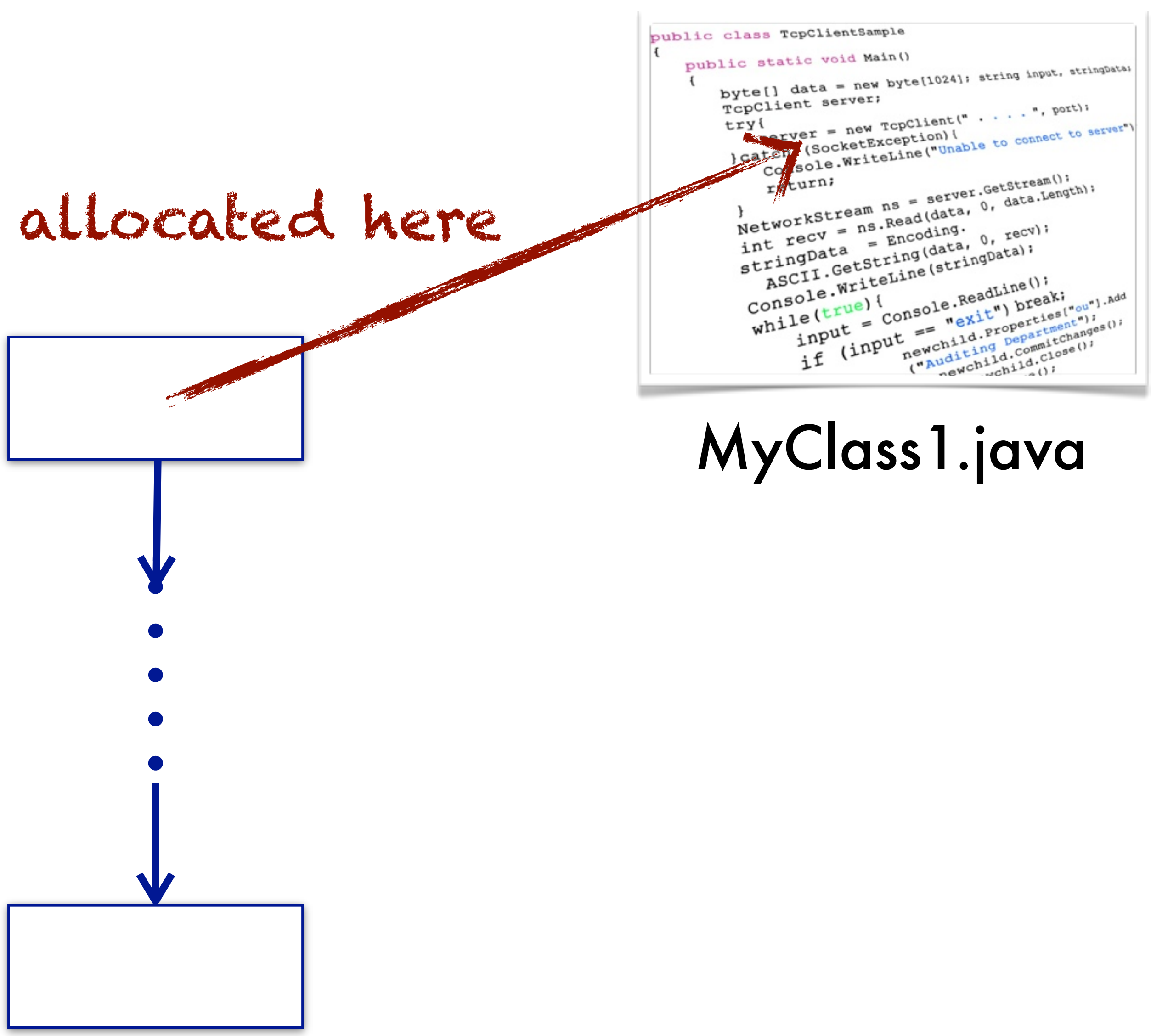
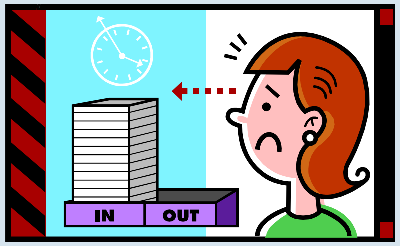
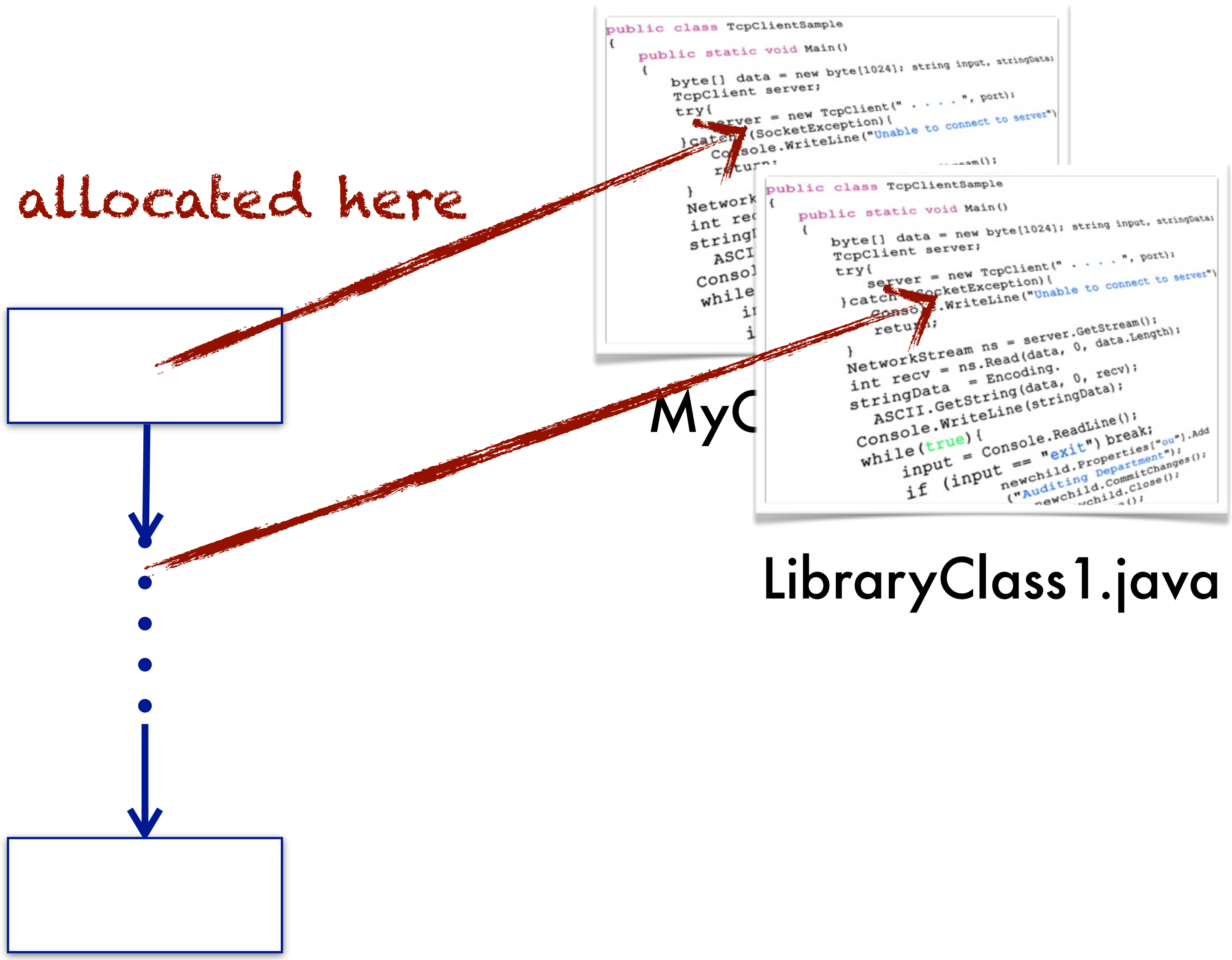




MyClass1.java

Manual triage is particularly hard for heap reachability reports.





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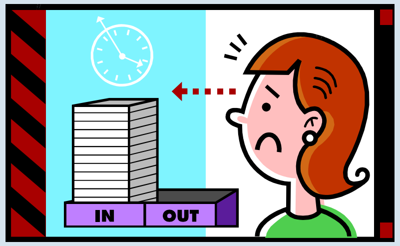

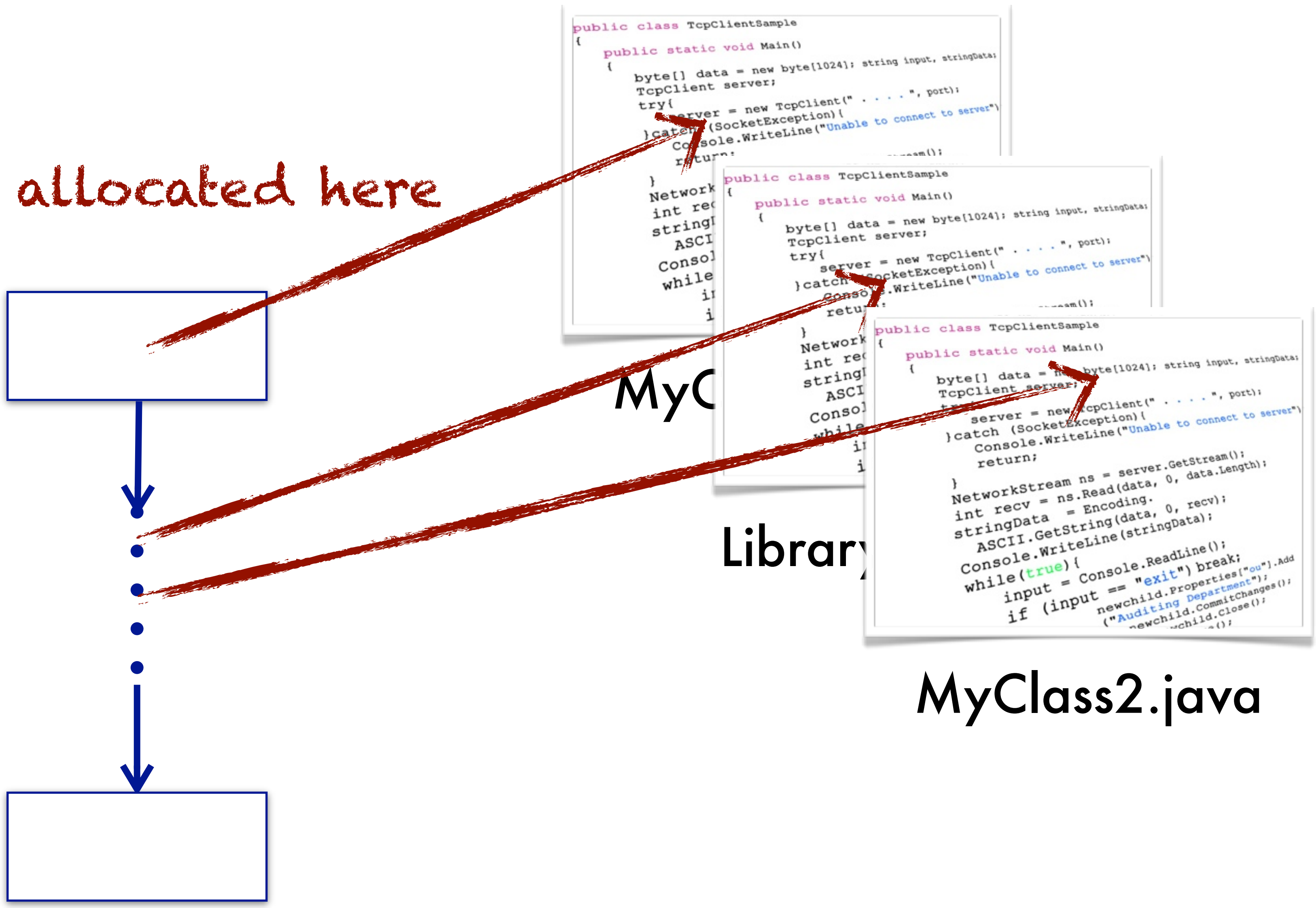

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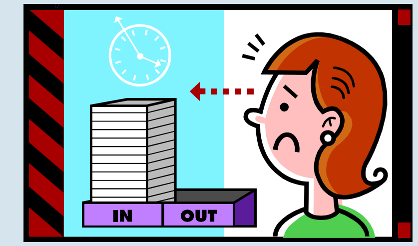

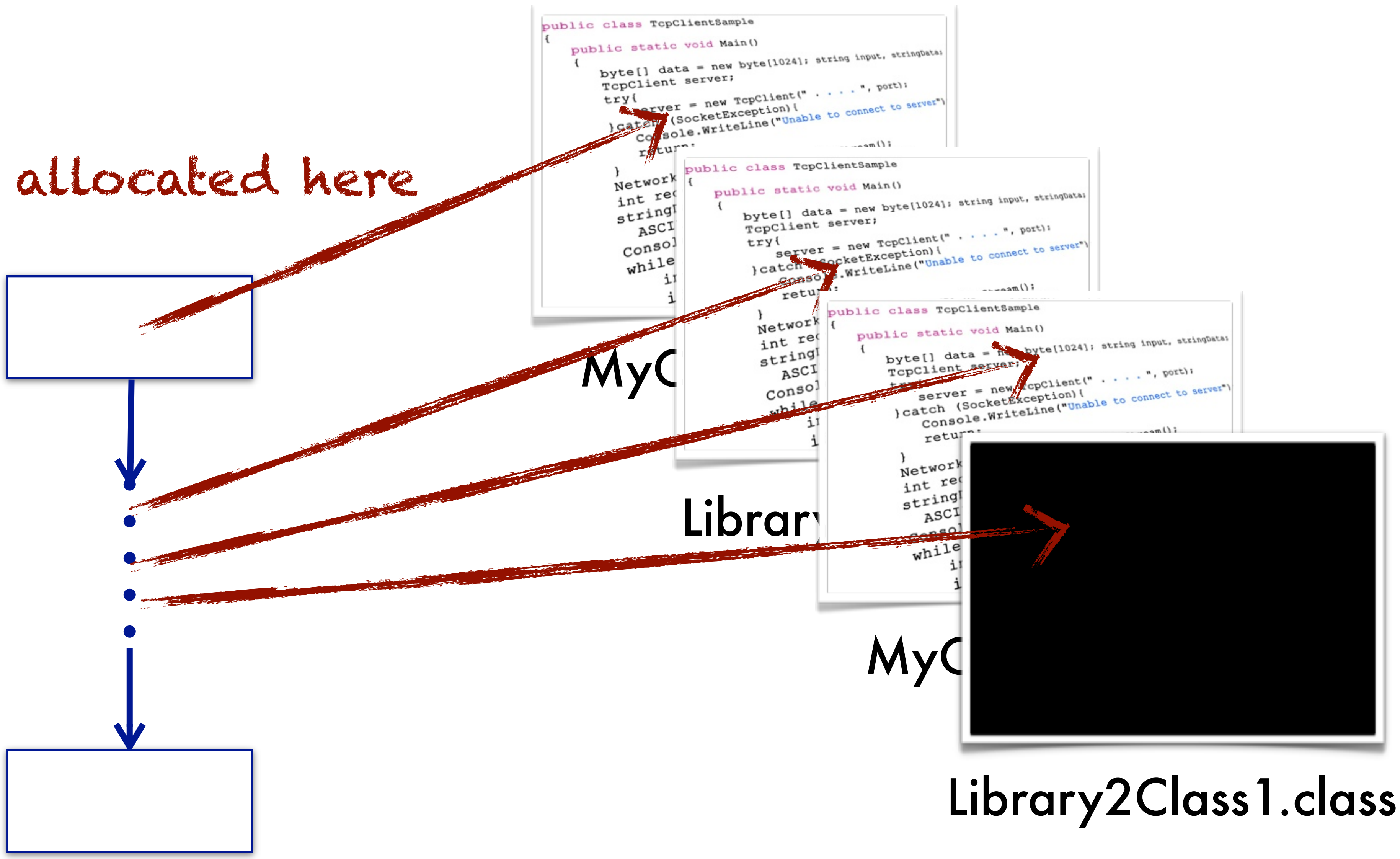

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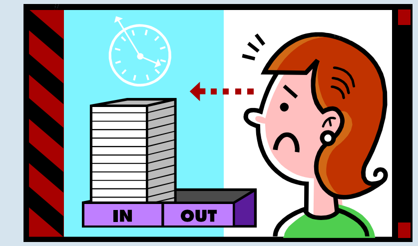

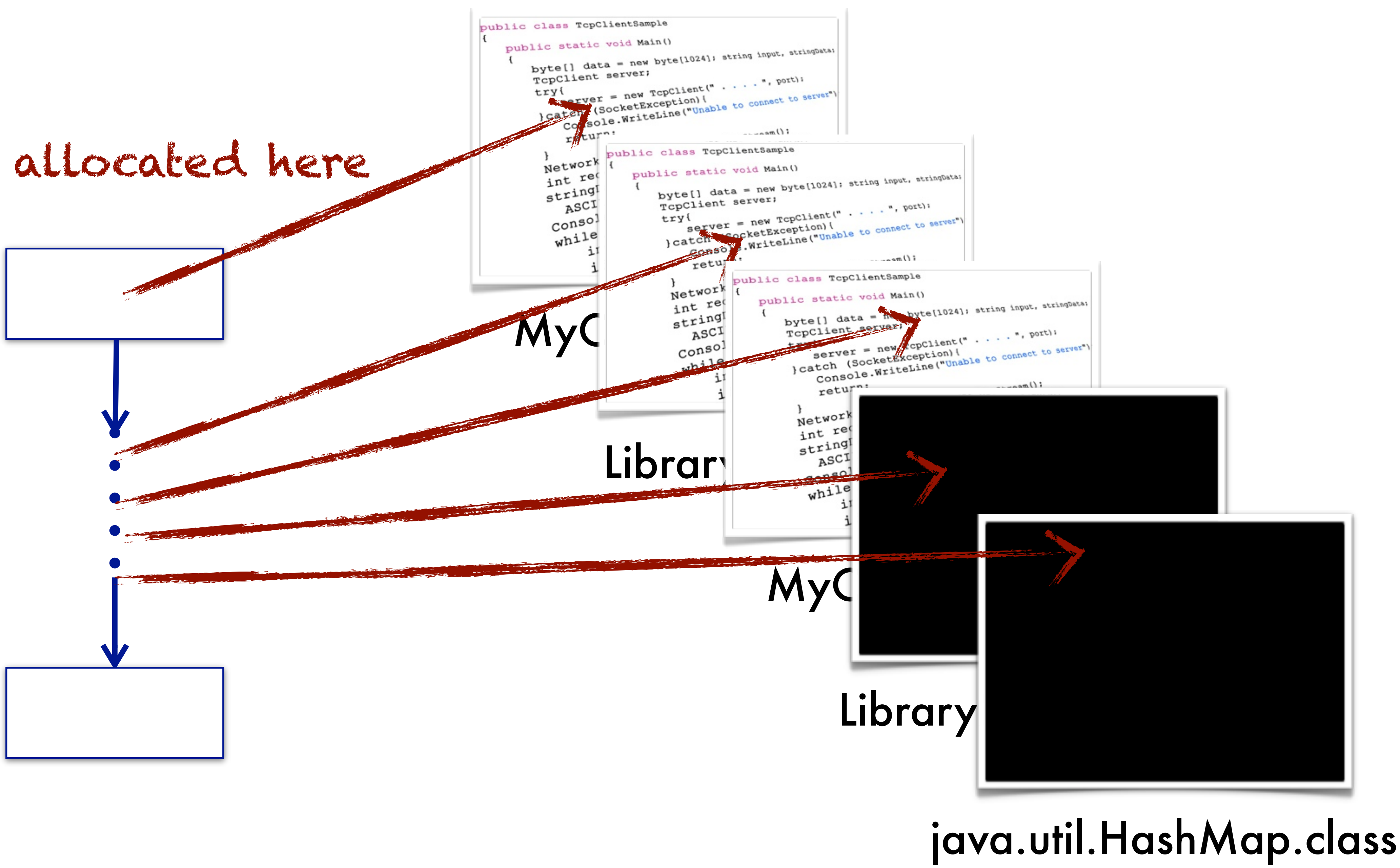

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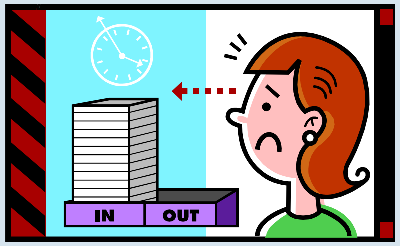

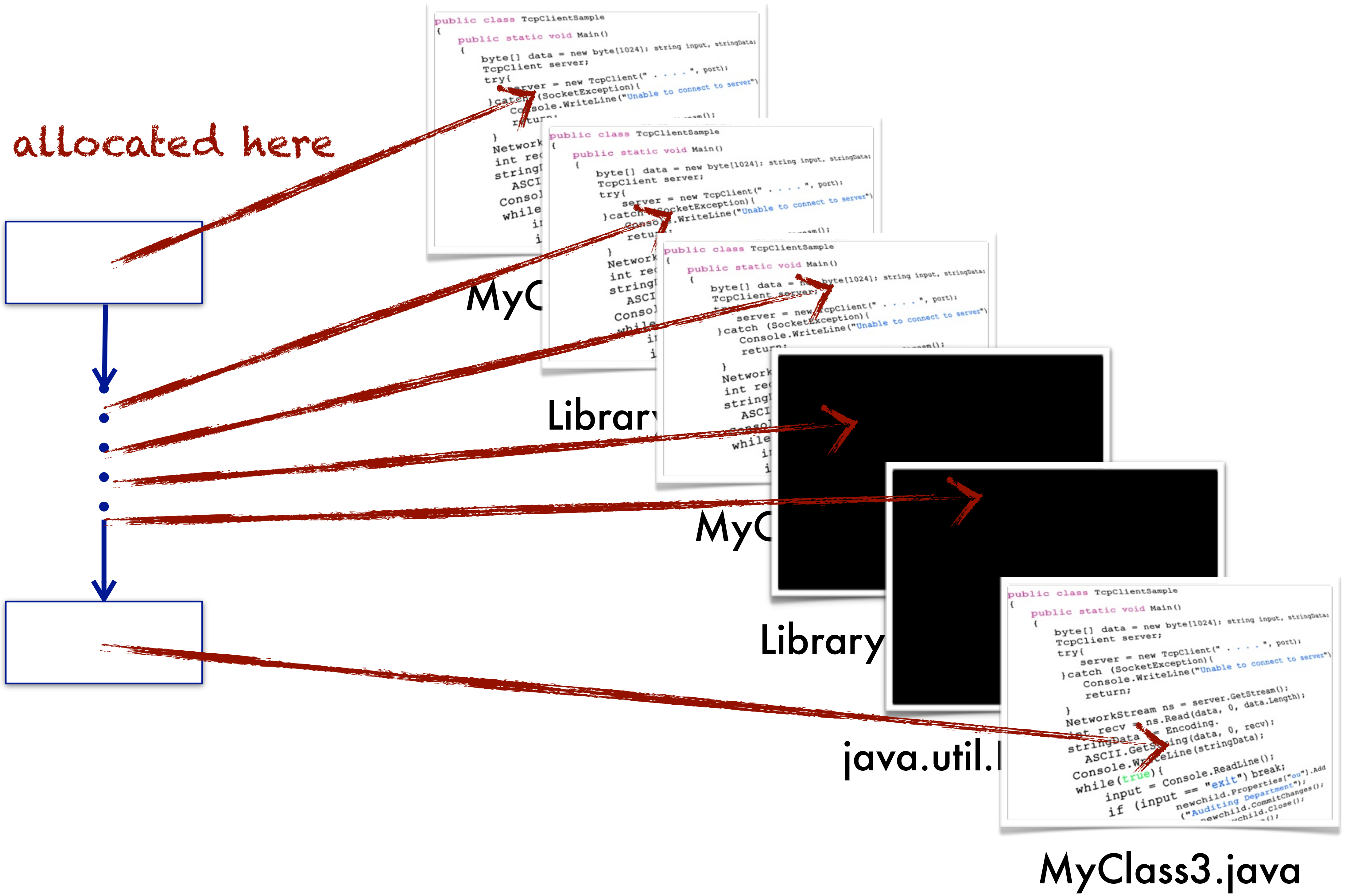

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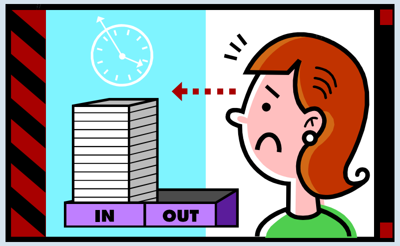
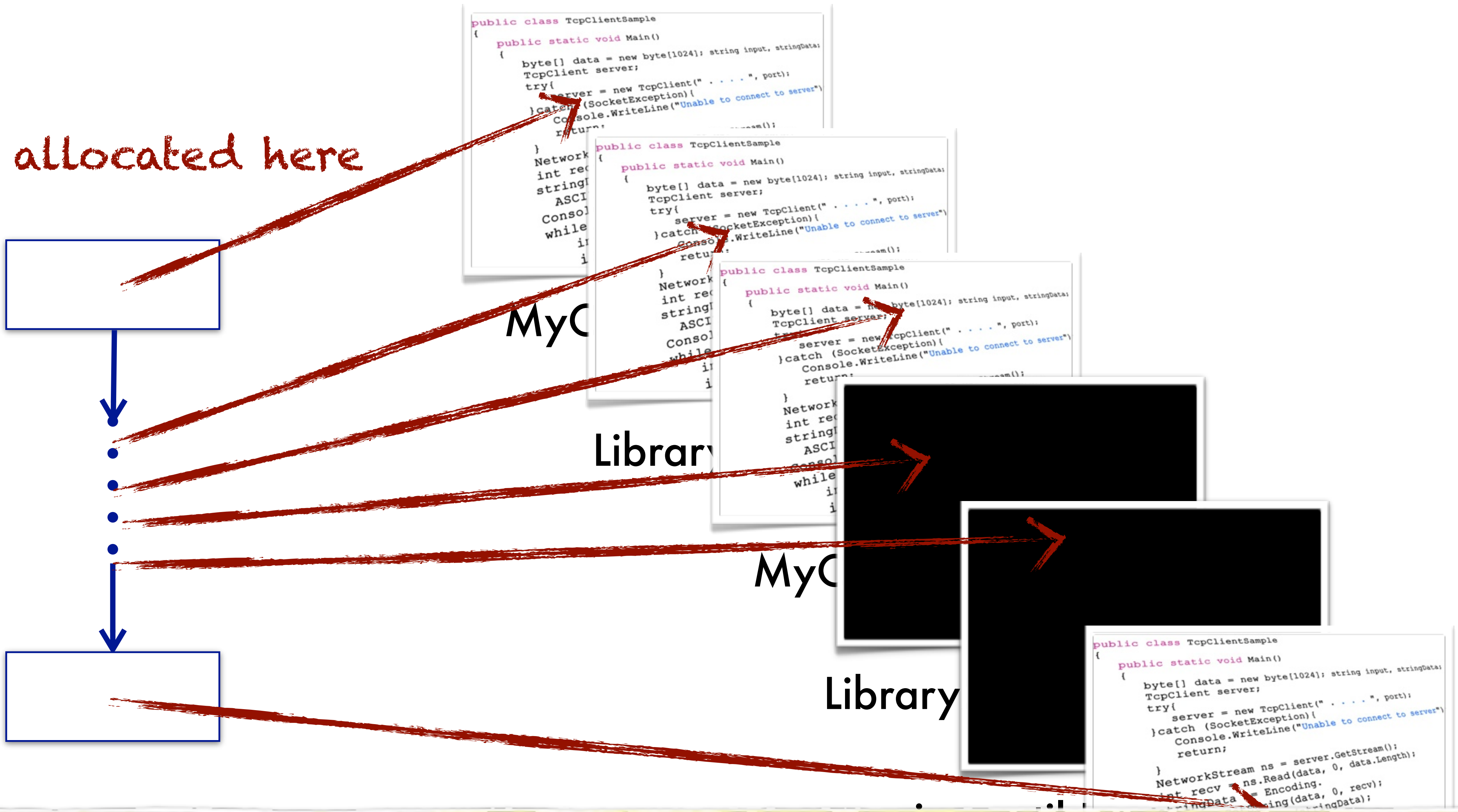
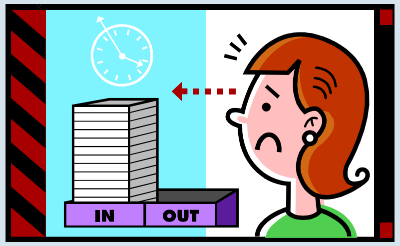




Get abstract heap path + maybe allocation sites
Guesstimate: >1 to 2 hours per alarm to triage "well"

Examining manual triage ...



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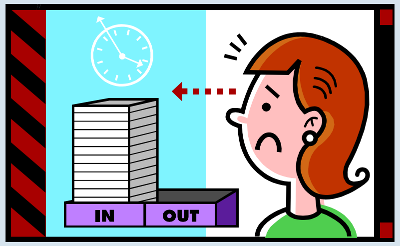

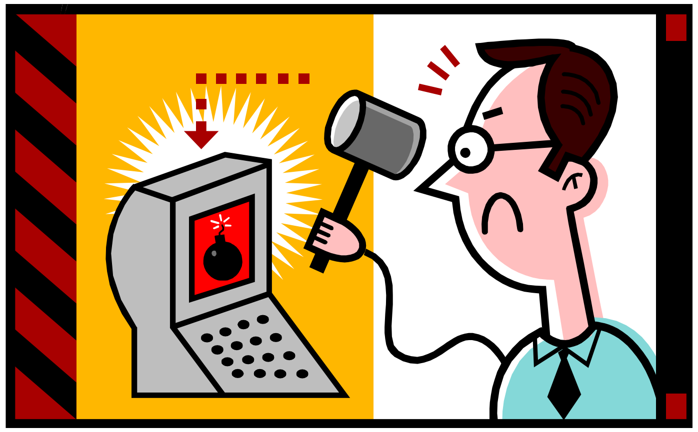

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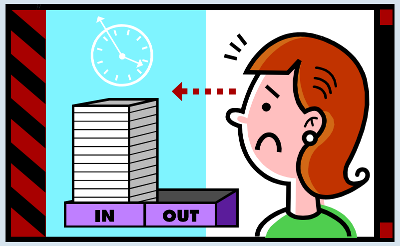

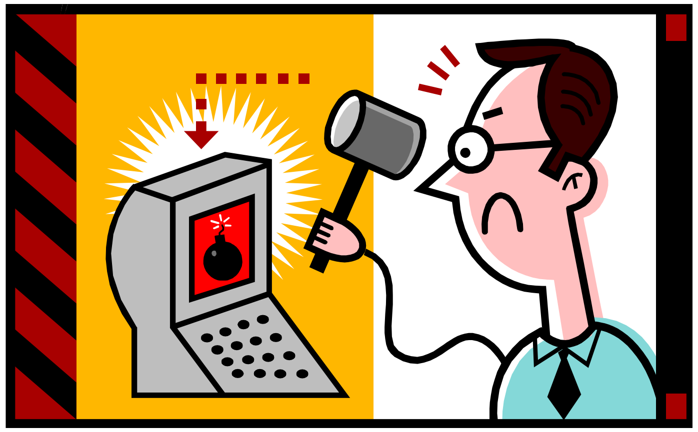

What does the user need to do with an alarm? He starts at, say, line 142 and traces back to see if a bug is possible given what's happening.

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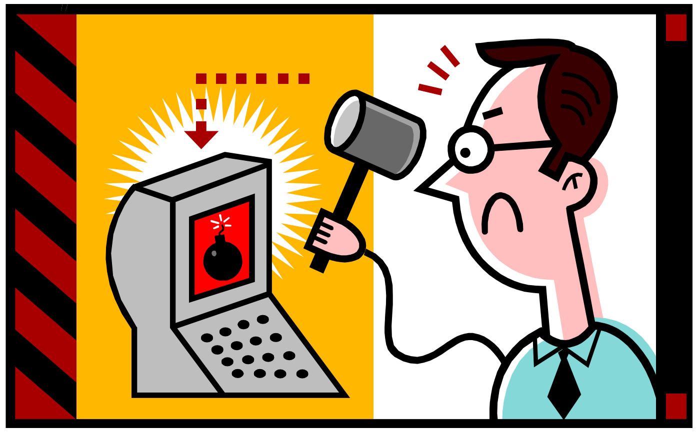

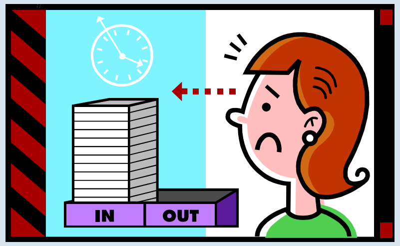

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We can do this with analysis!

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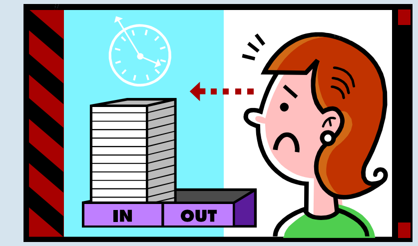

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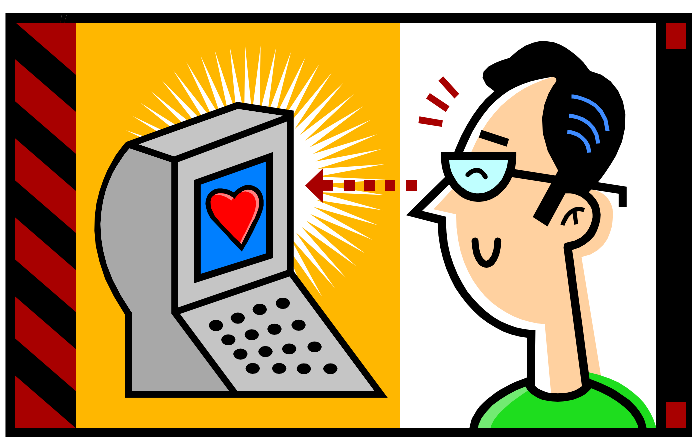

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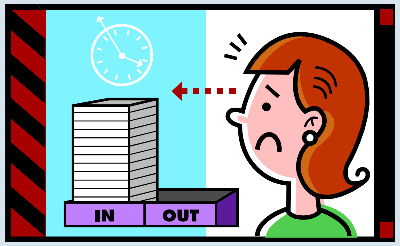

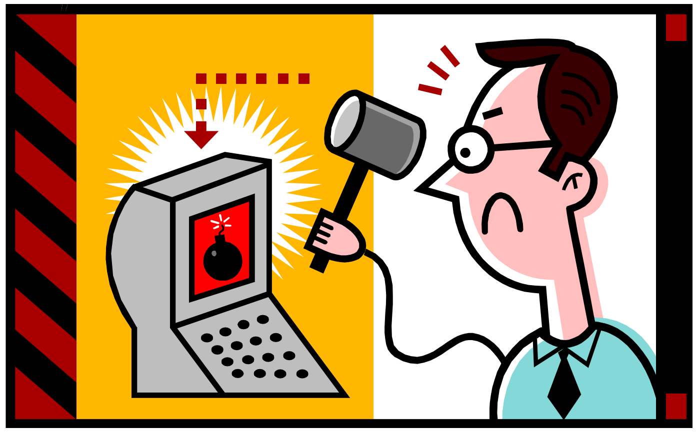

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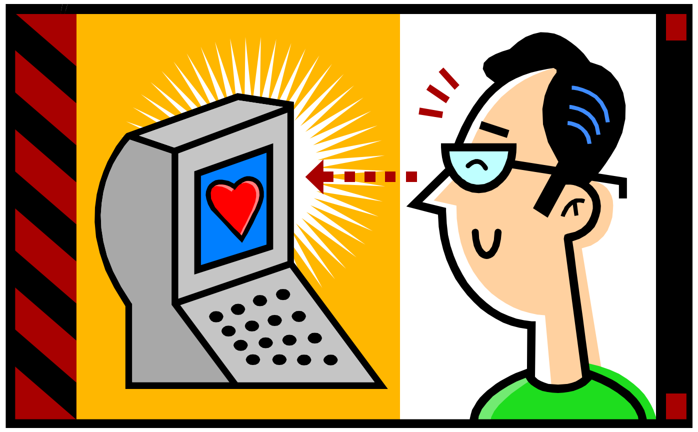
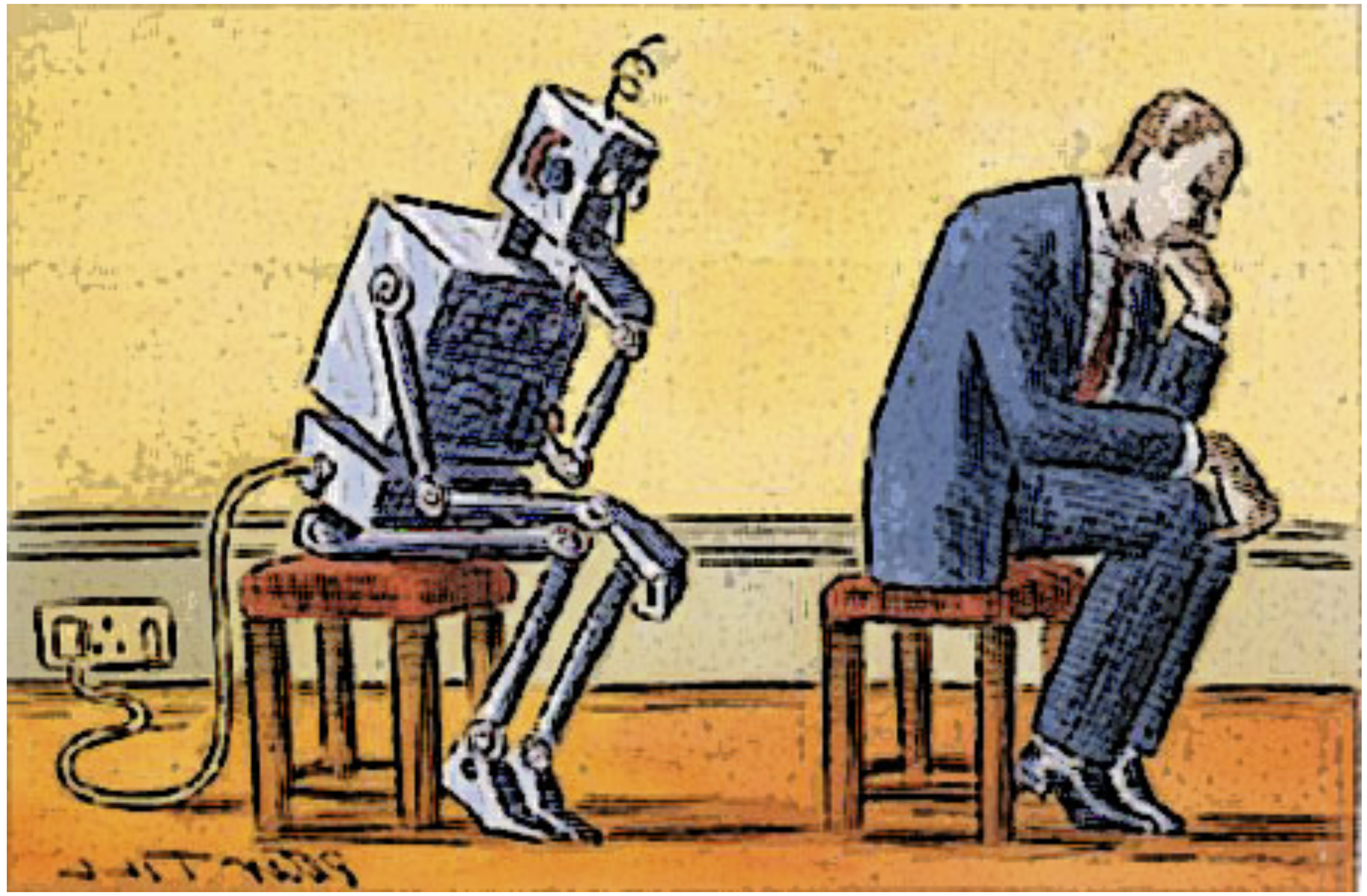
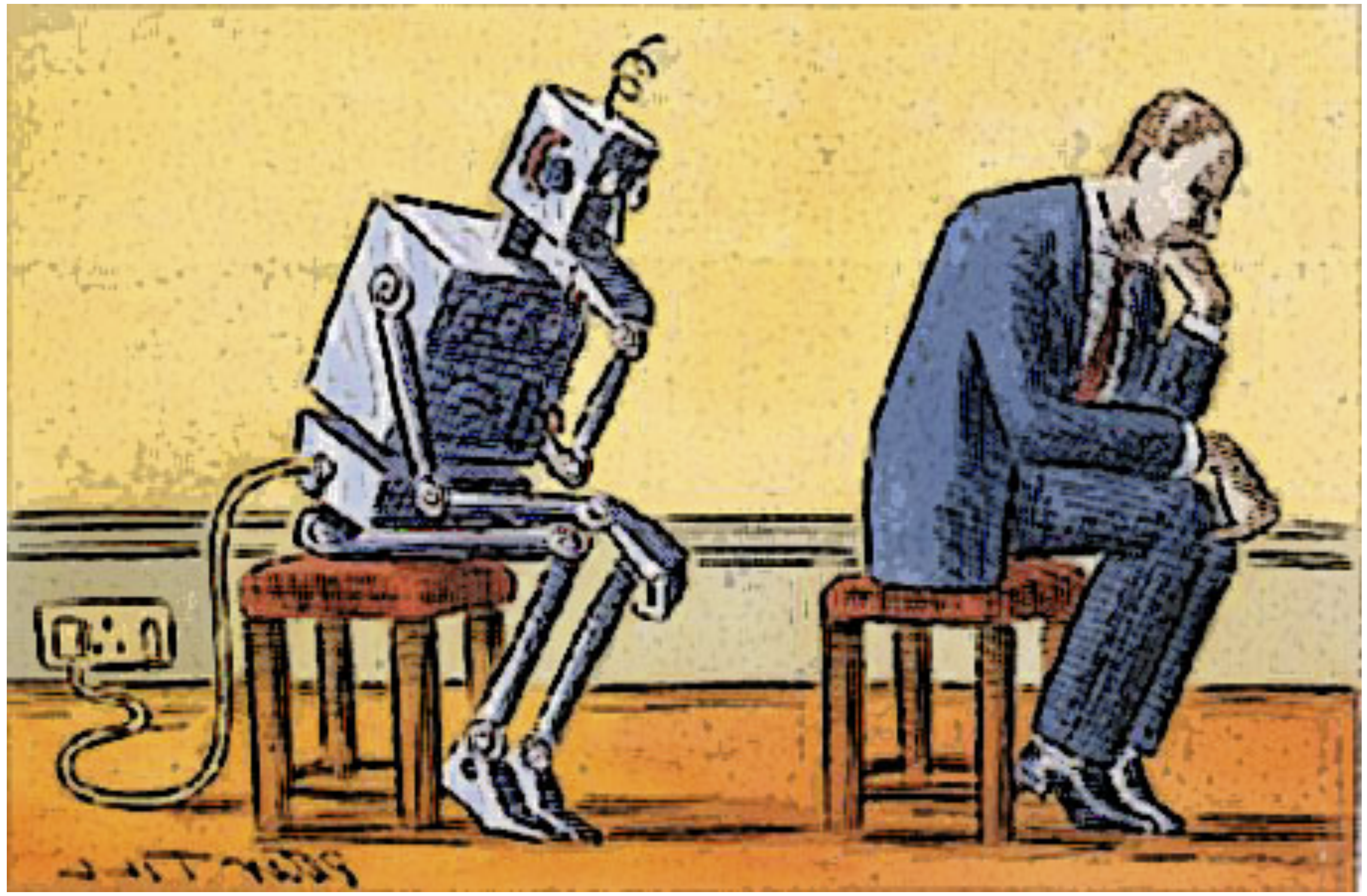
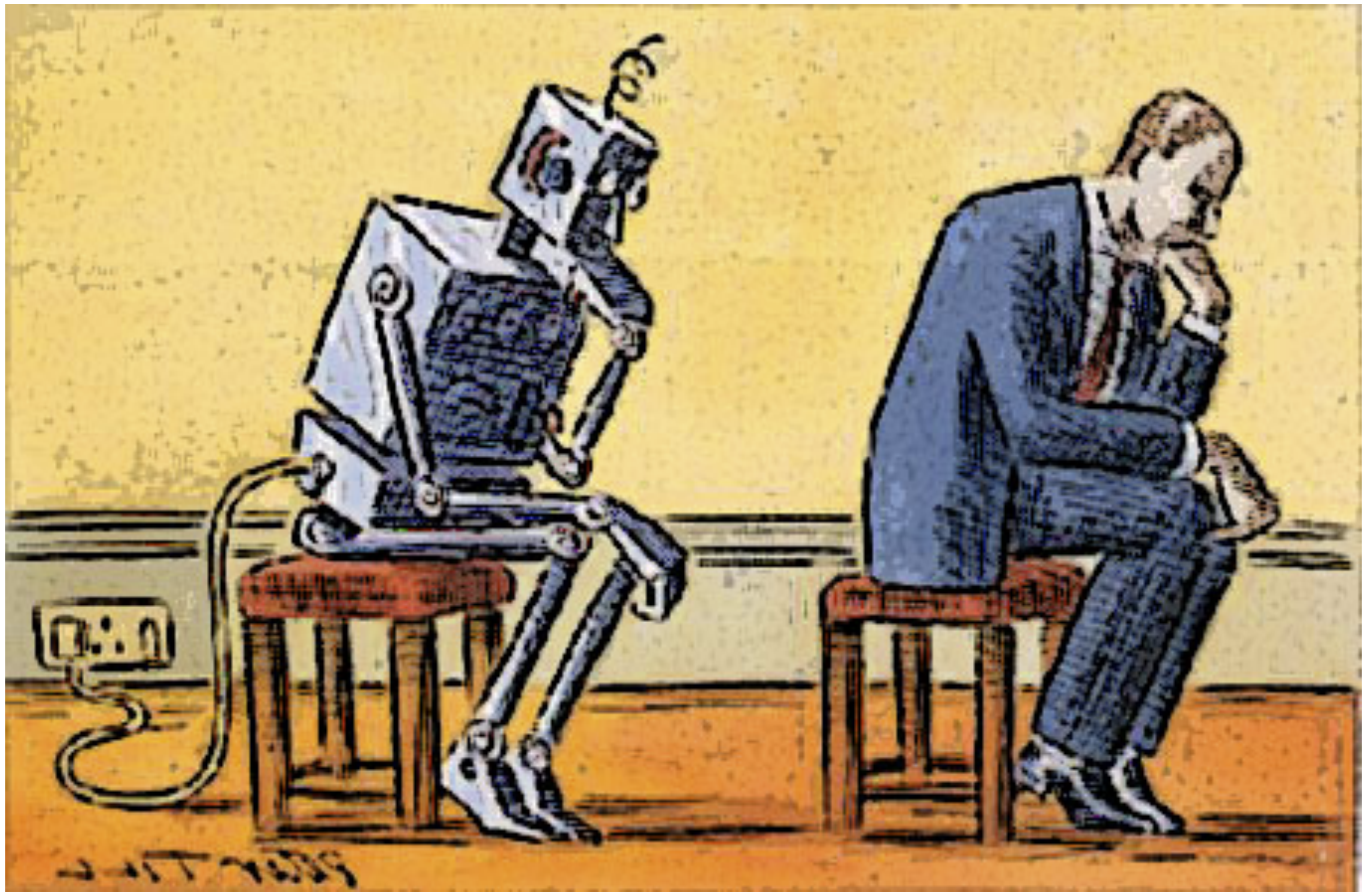


If we filter most false alarms, the user can triage more quickly and get to true bugs earlier (without frustration).





Automate the tasks that developers hate doing
But not the things they love



Design an algorithm for

Automate the tasks that developers hate doing
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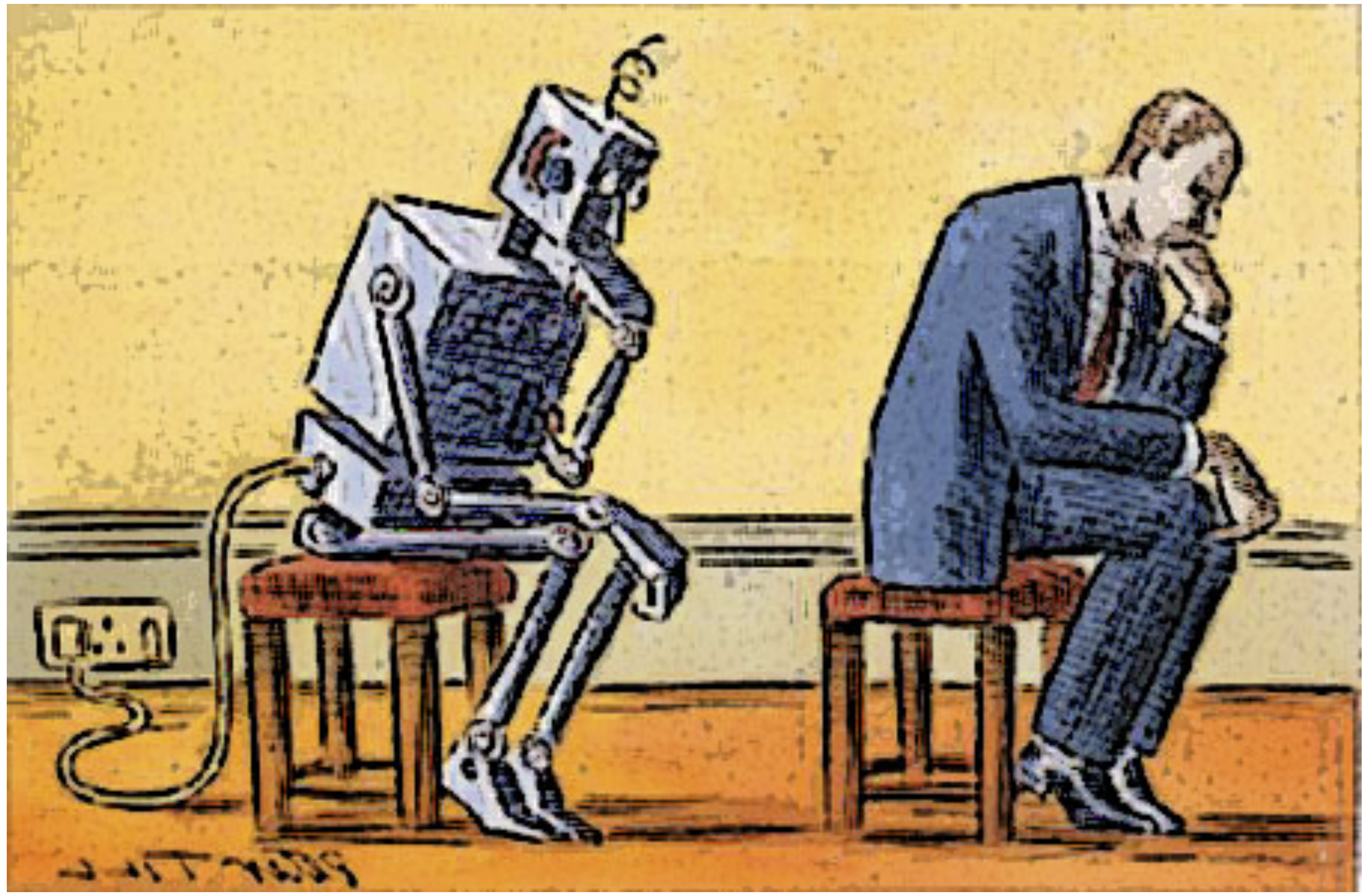
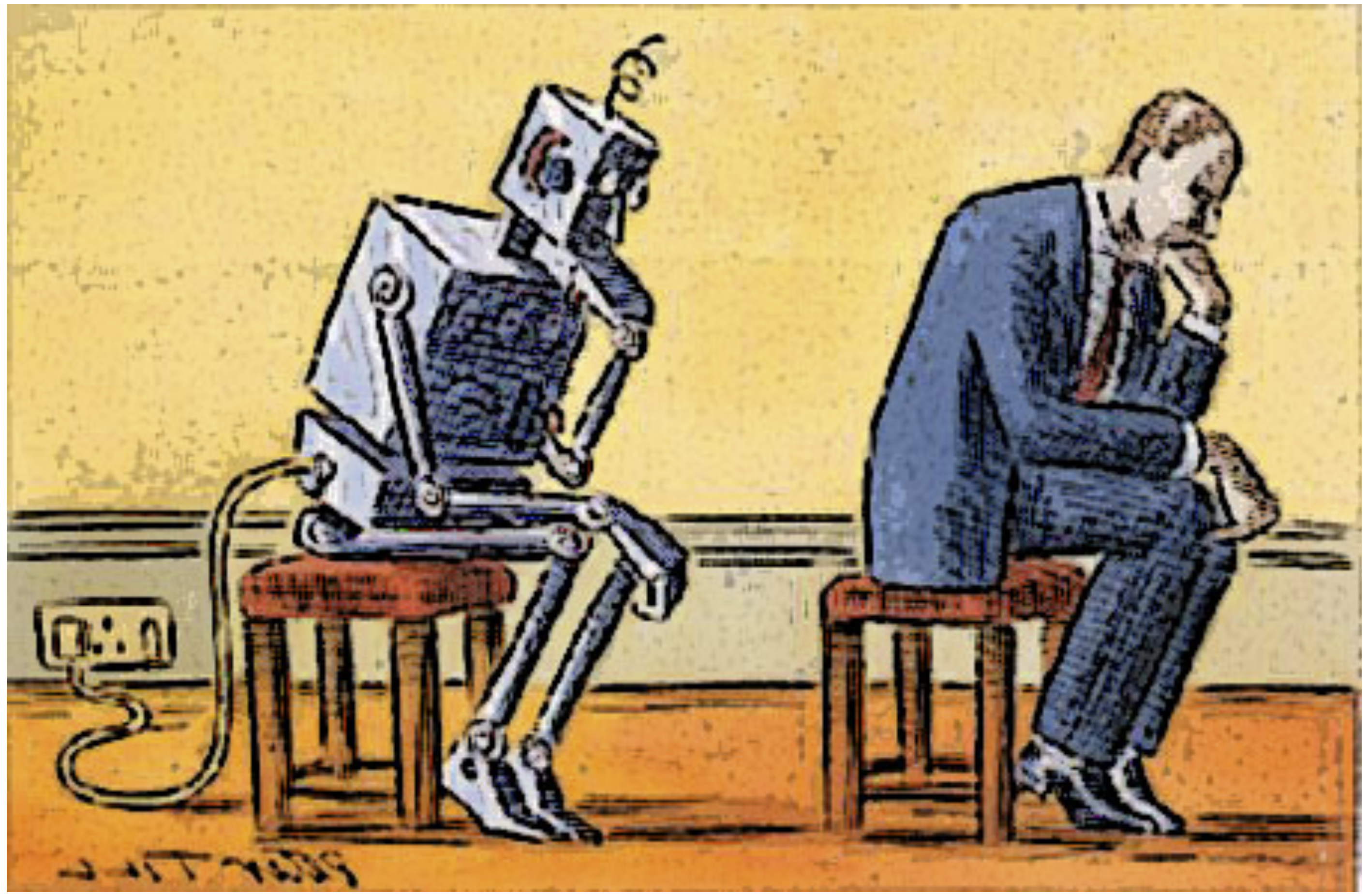


Automate the tasks that developers hate doing
But not the things they love

require human
creativity and insight



Automate the tasks that developers hate doing
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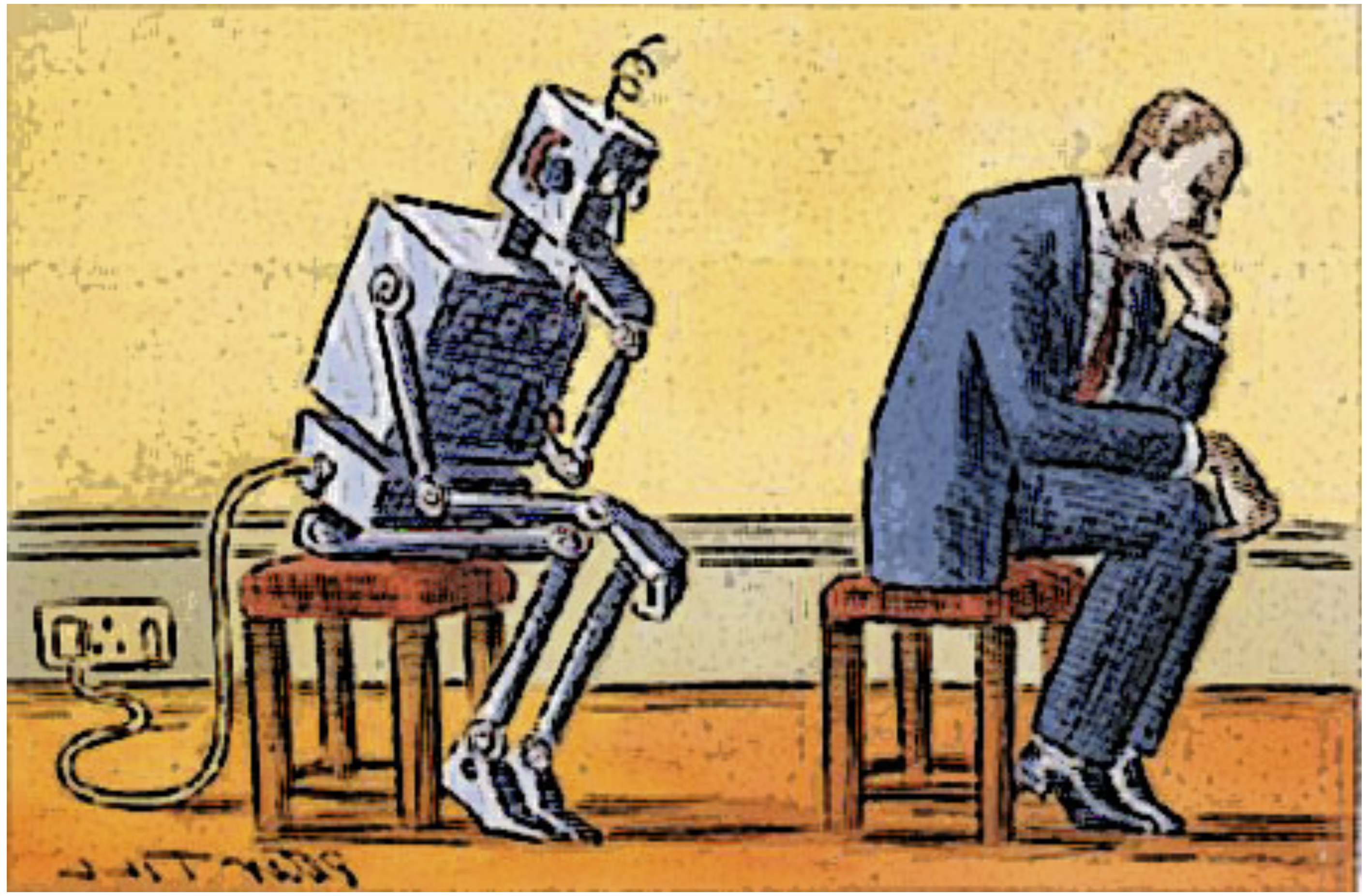
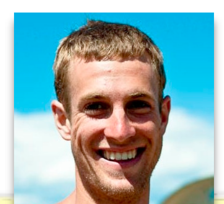
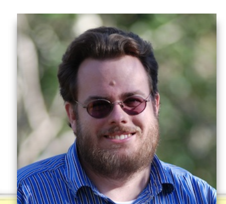
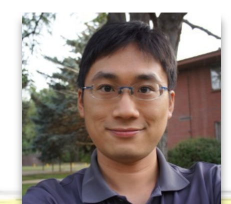


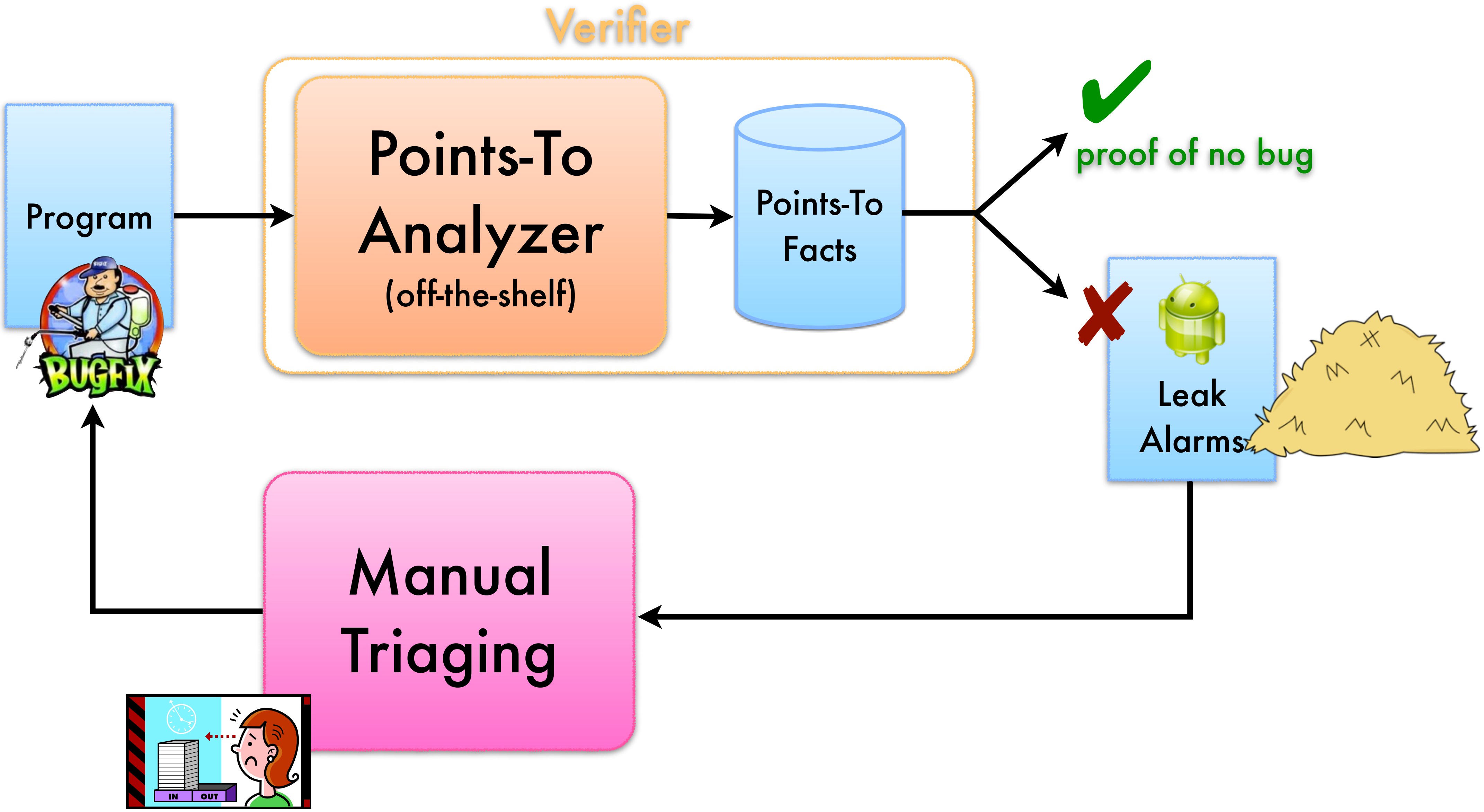
   

my graduate students

Automate the tasks that ~~developers~~ hate doing

But not the things they love

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



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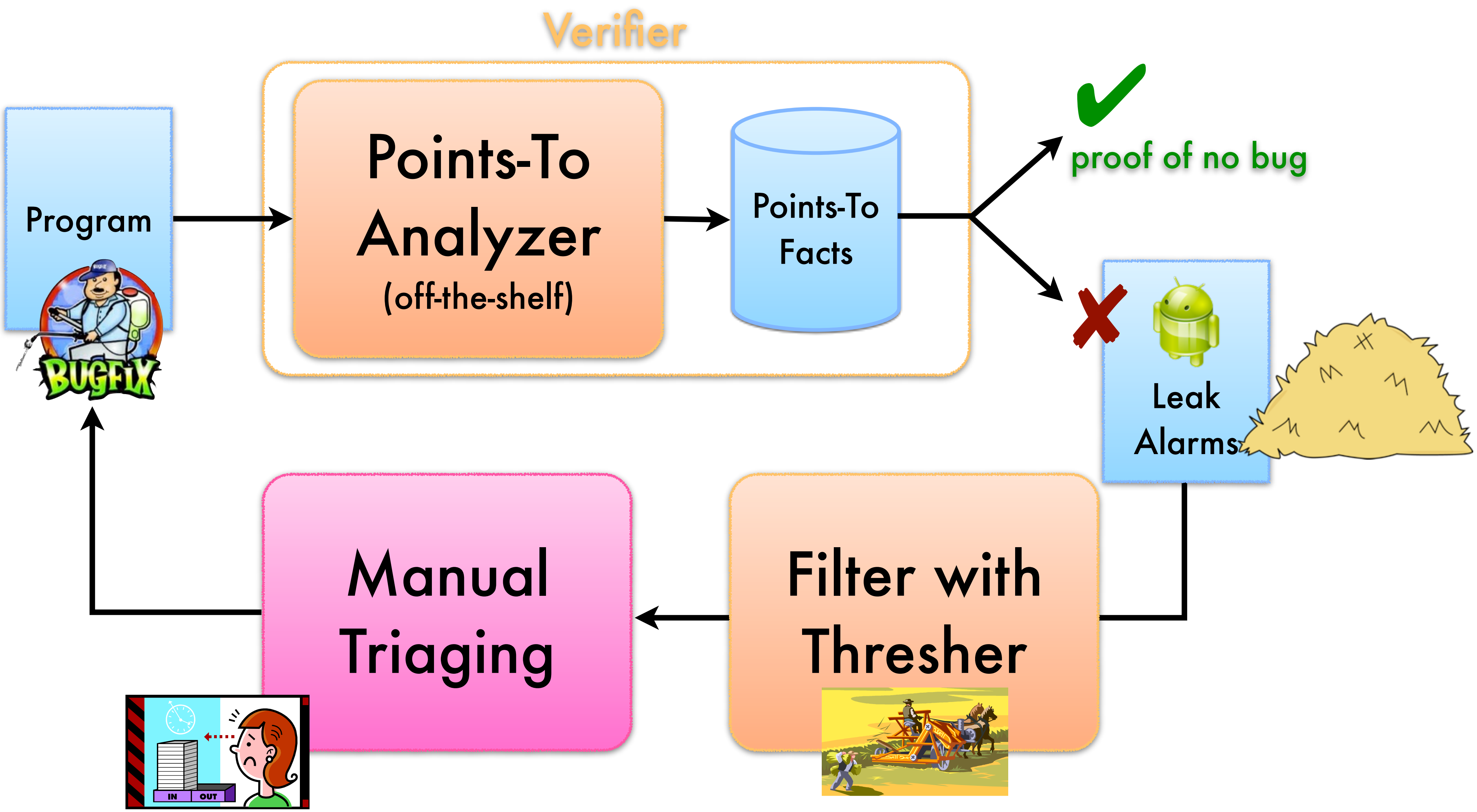

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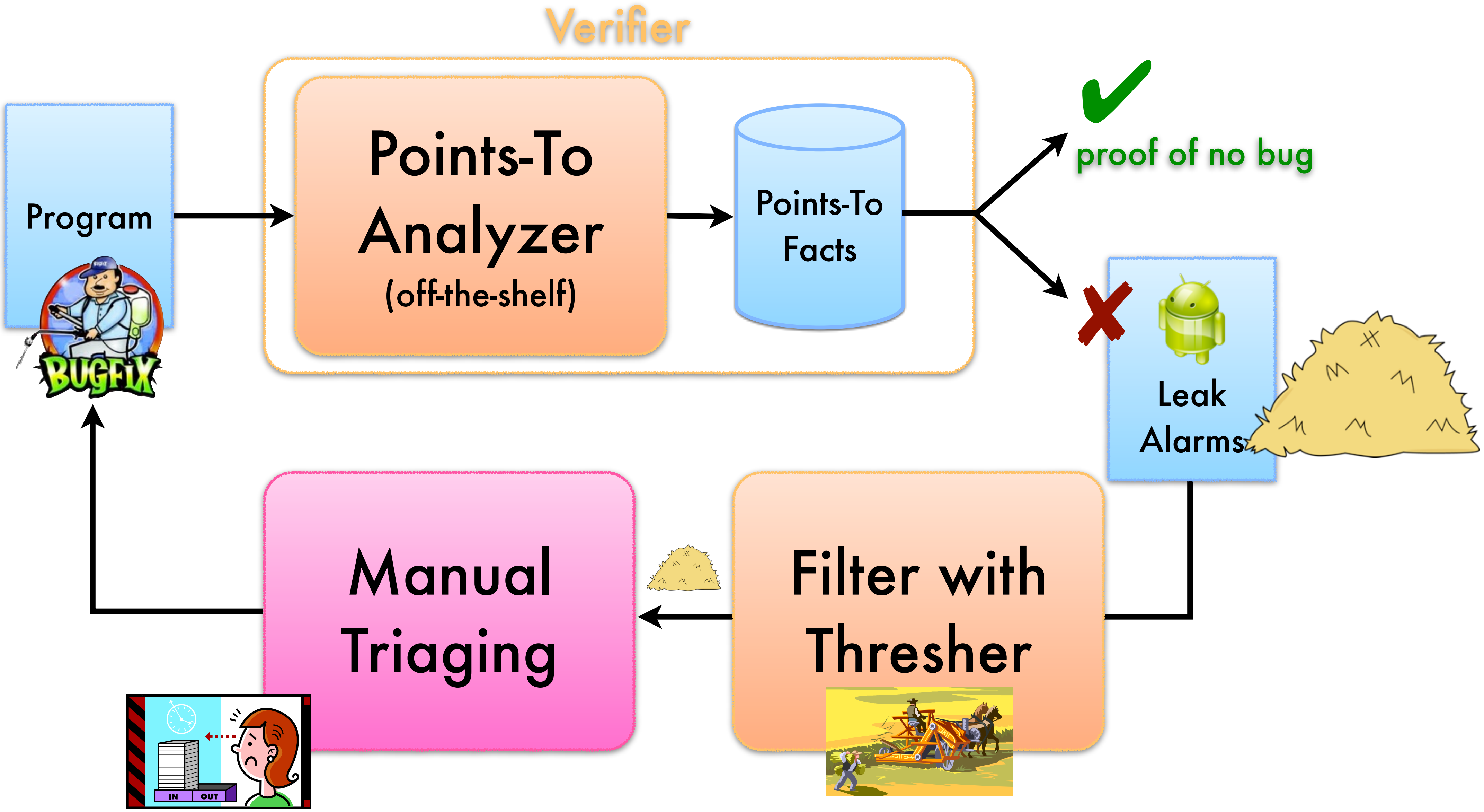

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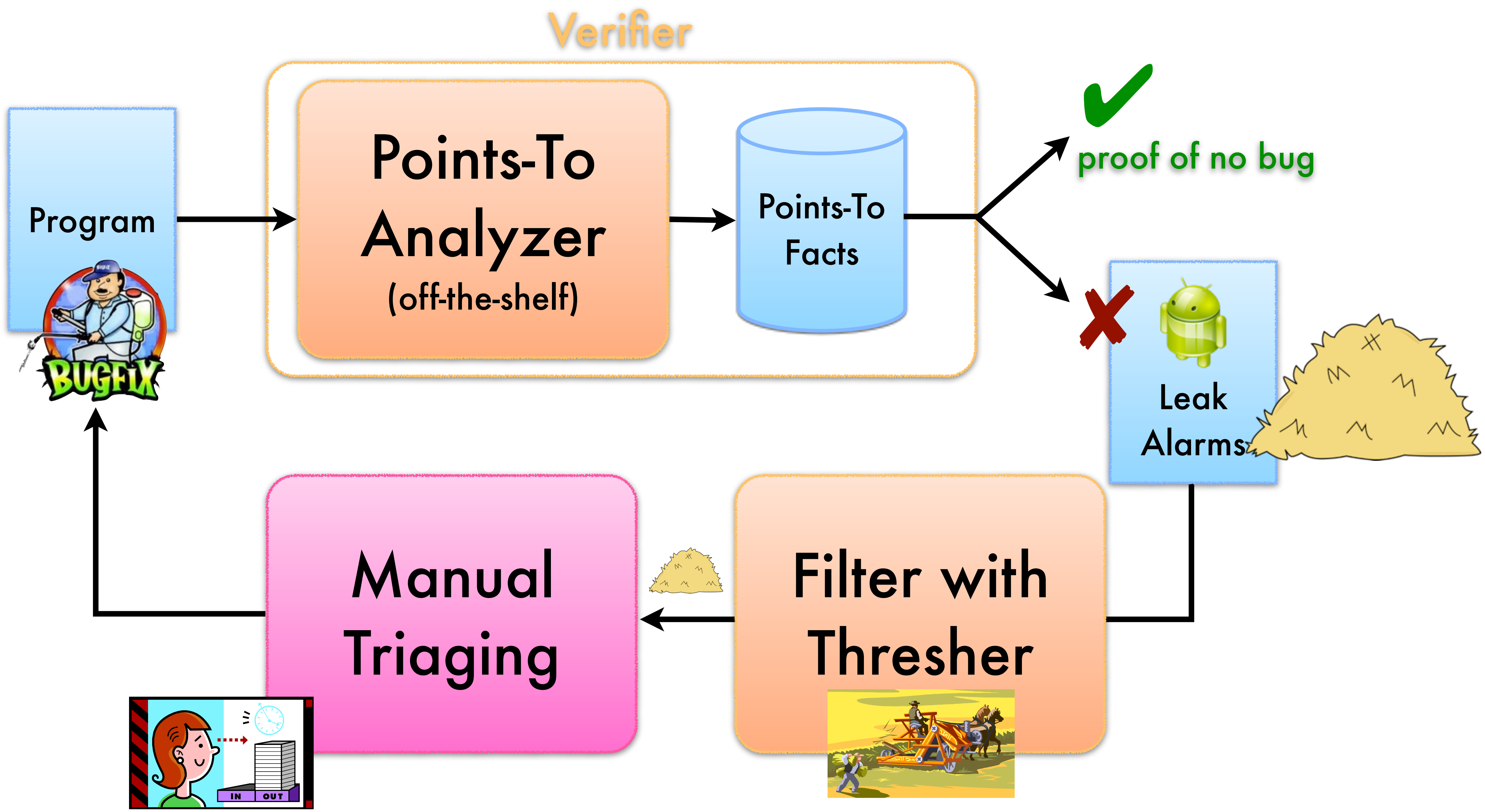

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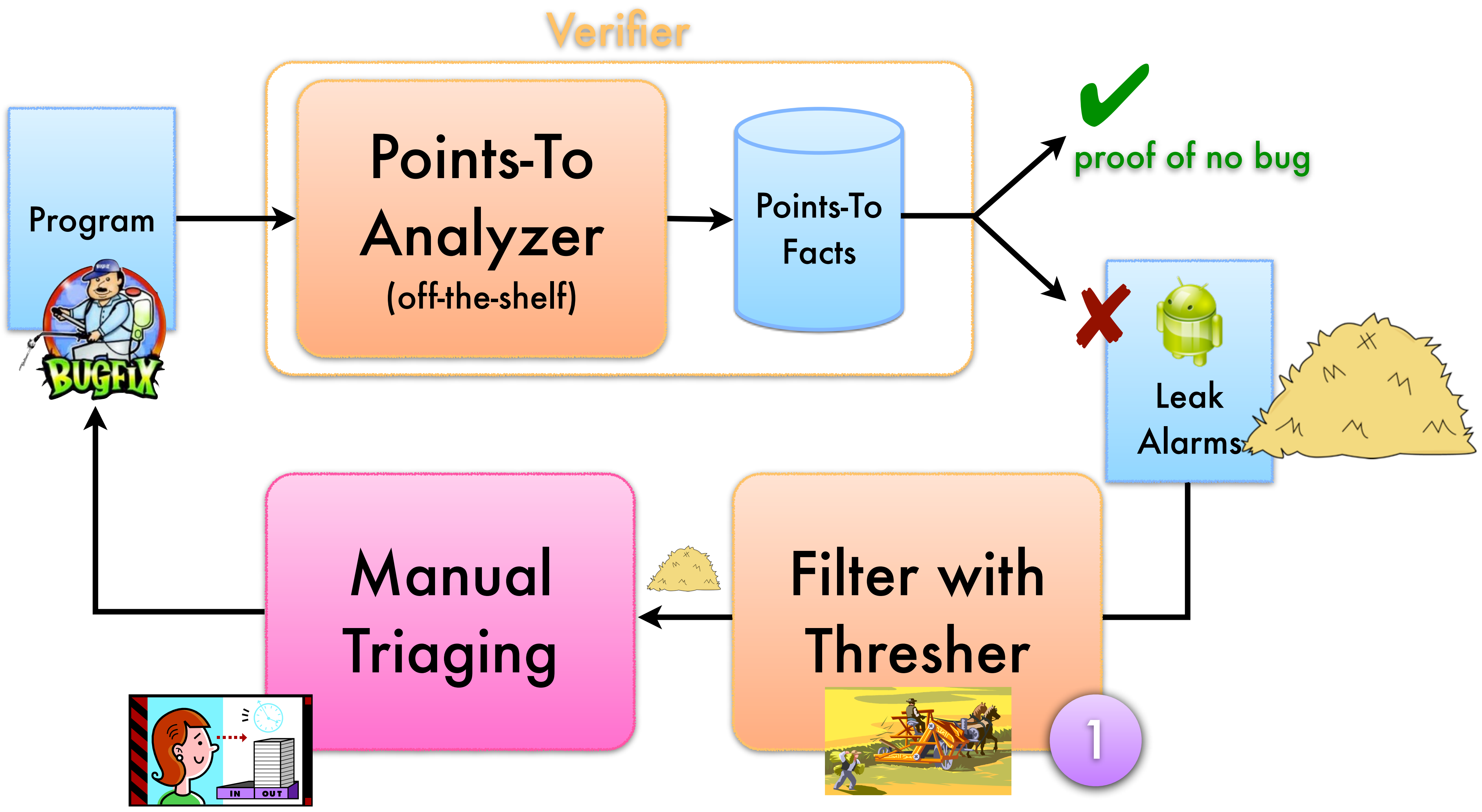
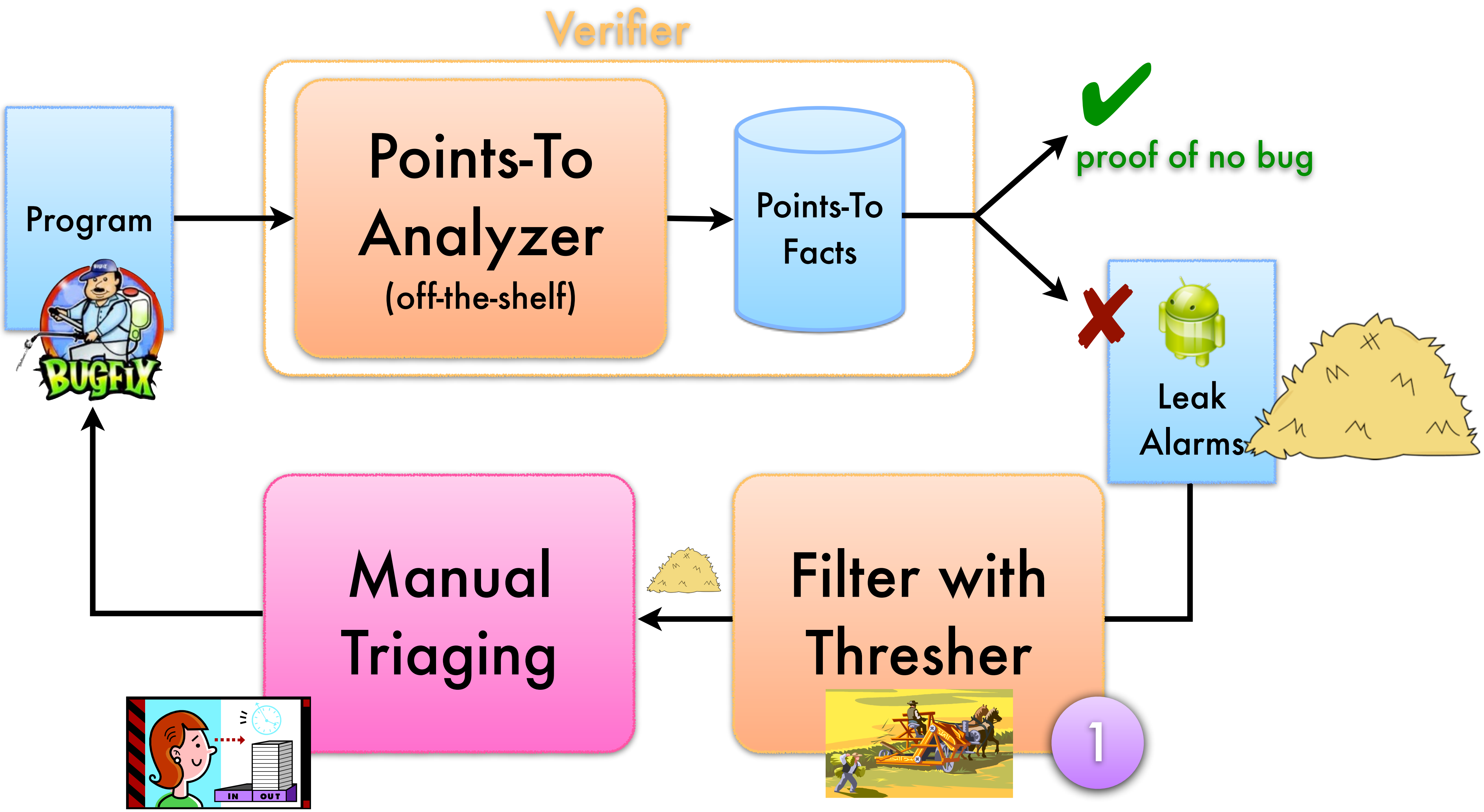


Idea 1: Refute points-to on-demand with second "uber-precise" filter analysis

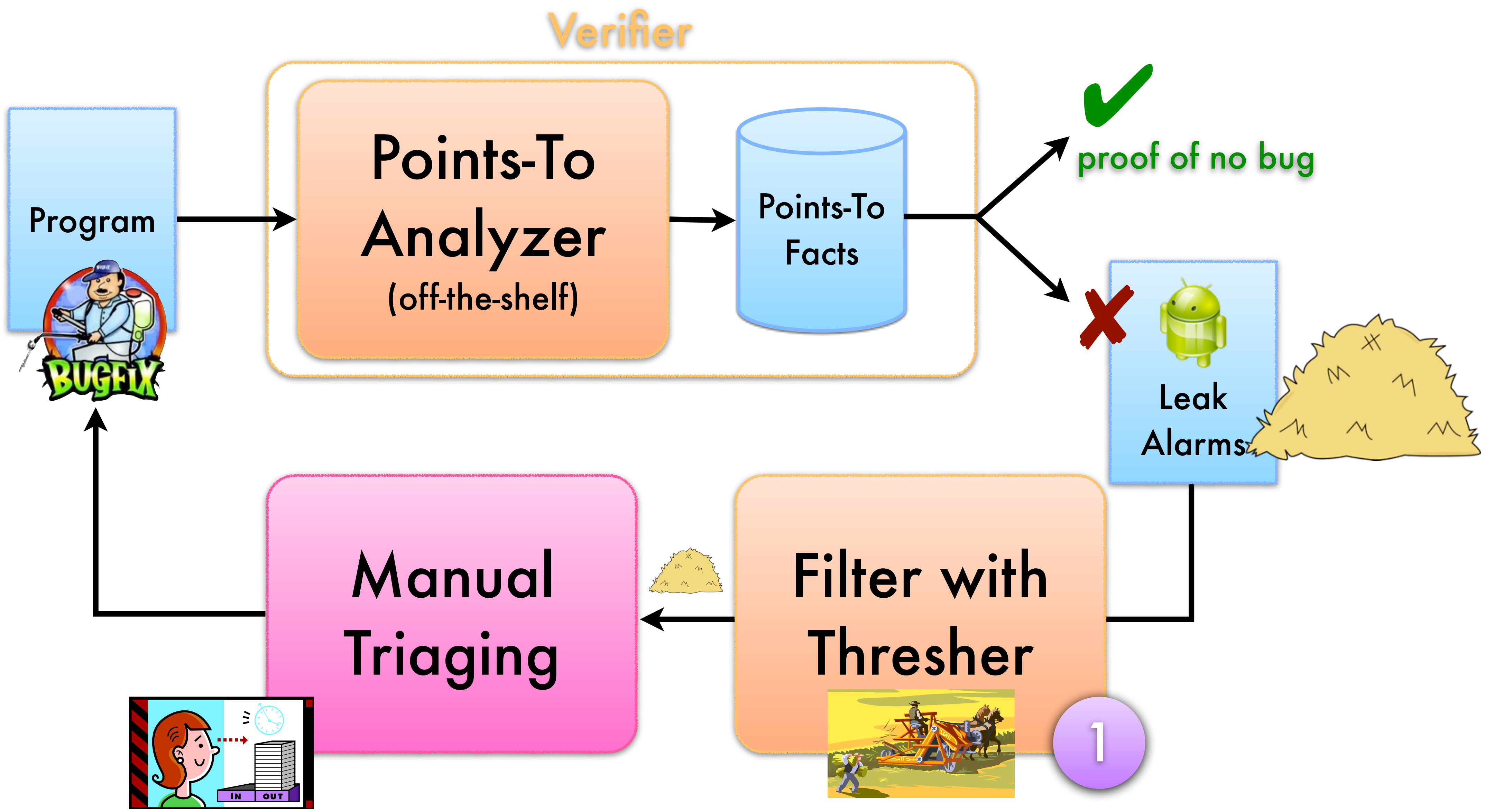
Thresher **filters** out false alarms by refuting them one-by-one.



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

*-sensitive

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



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

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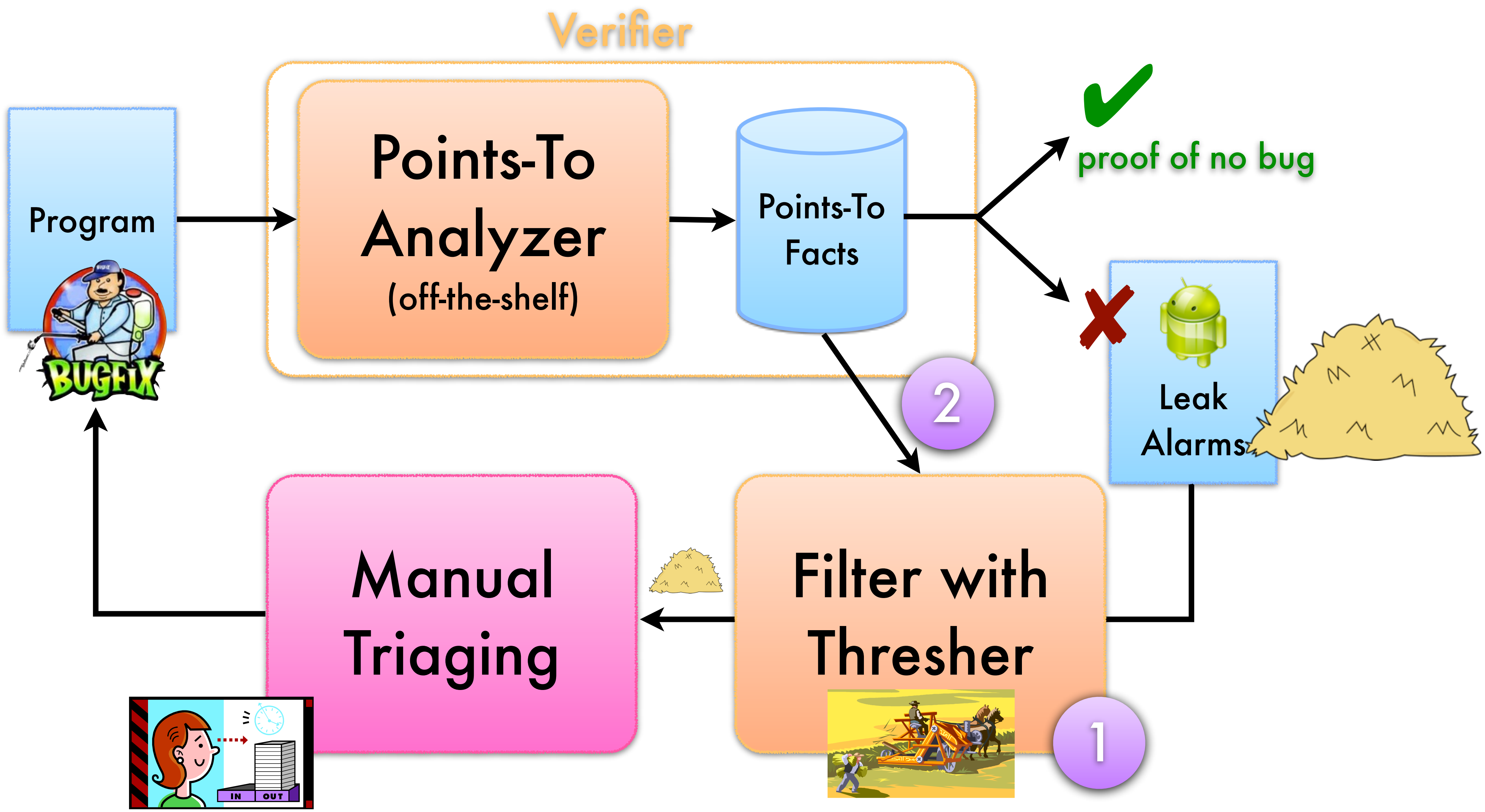

Idea 1: Refute points-to on-demand with second "uber-precise" filter analysis

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

1

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

$$\boxed{o} \to \boxed{o'} \to \cdots \to \boxed{}$$

of type T .

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

1

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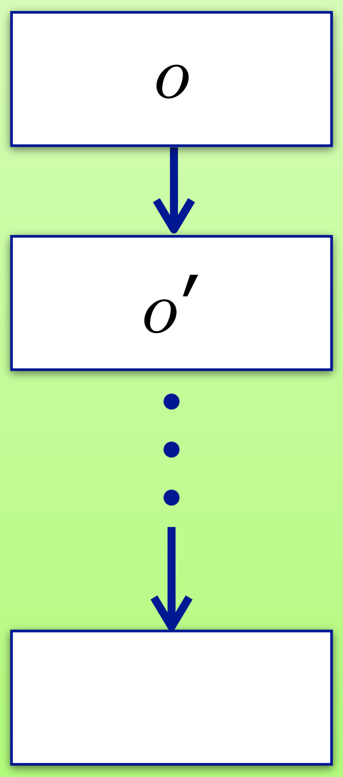

of type T .

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

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

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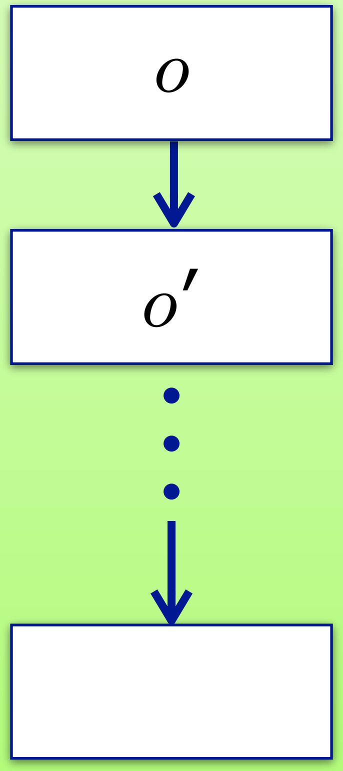

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A. Why does object o possibly point to o' ?

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

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

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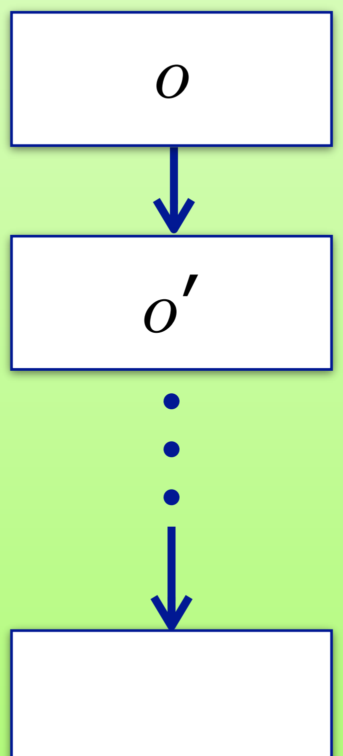

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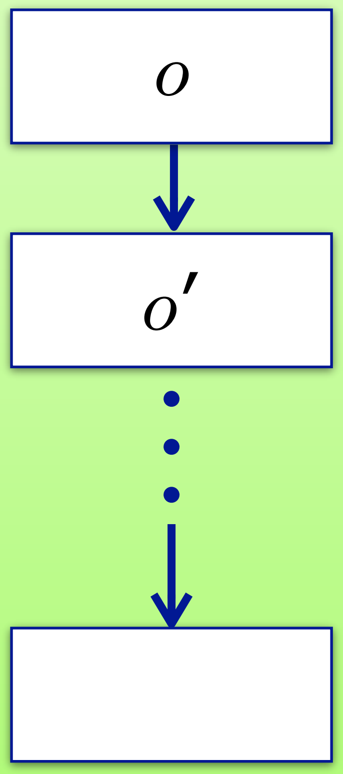

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A. Why does object o possibly point to o' ?

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

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

o

$\downarrow$

o'

⋮

$\downarrow$

of type T .

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

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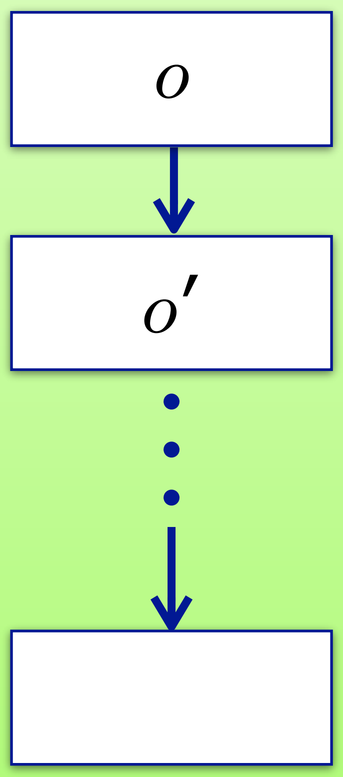

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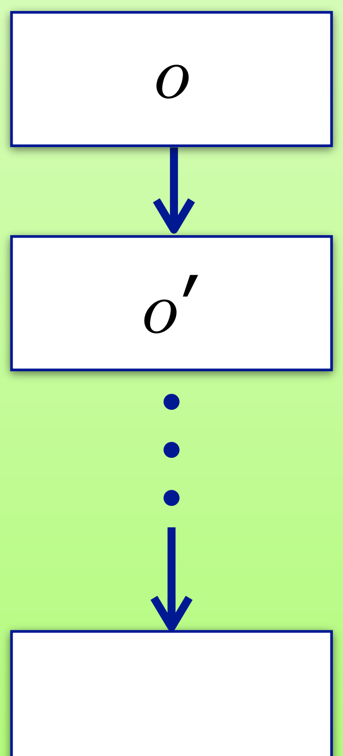

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A just asks "but why?"

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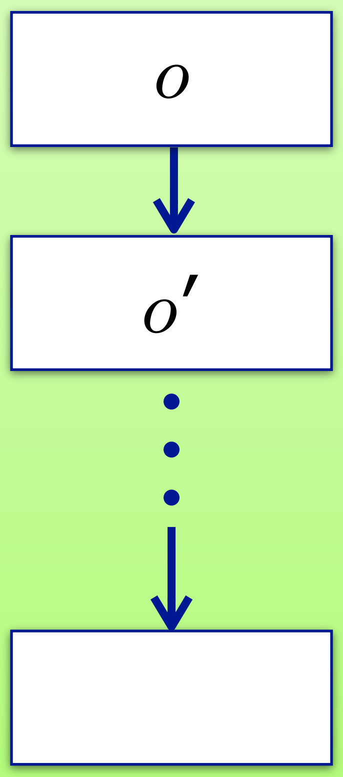

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B. Because before the previous statement s', the state could satisfy formula φ'

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

B. Because before statement s, the program state could satisfy formula φ

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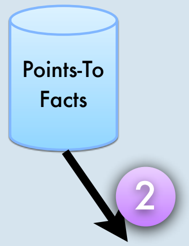
Leverage first analysis by designing specialized constraint forms



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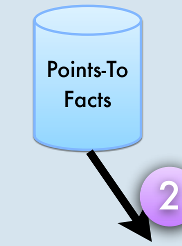

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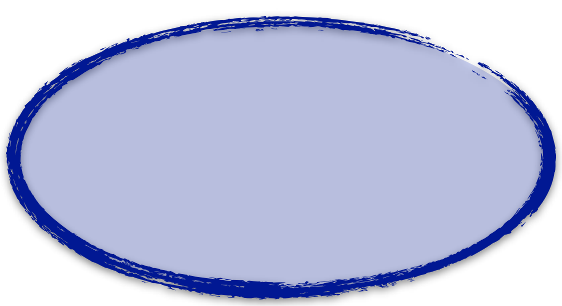

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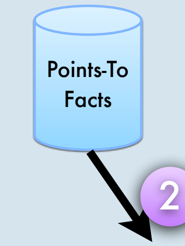

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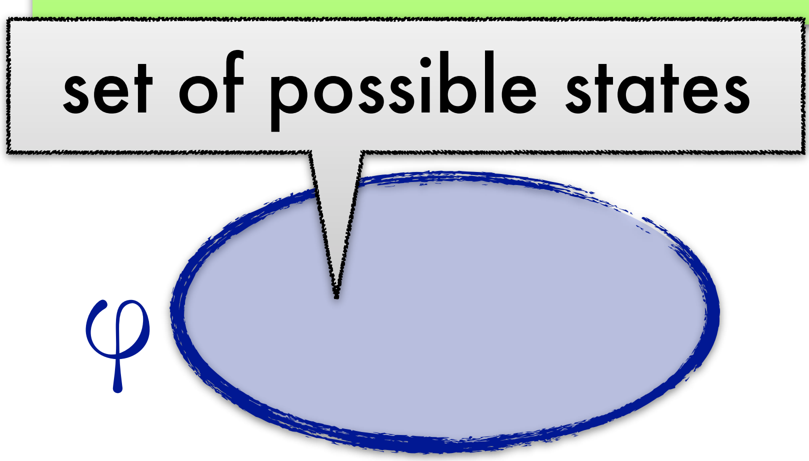

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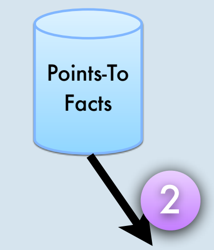

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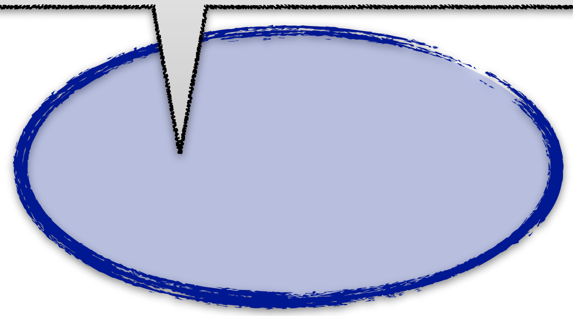
B. ... statement s', ... a φ'

if empty, then refuted (A wins)

set of possible states

φ



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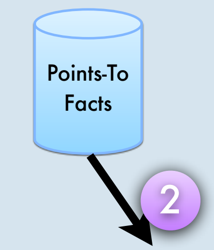

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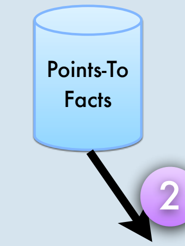

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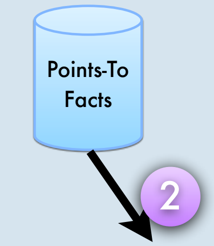

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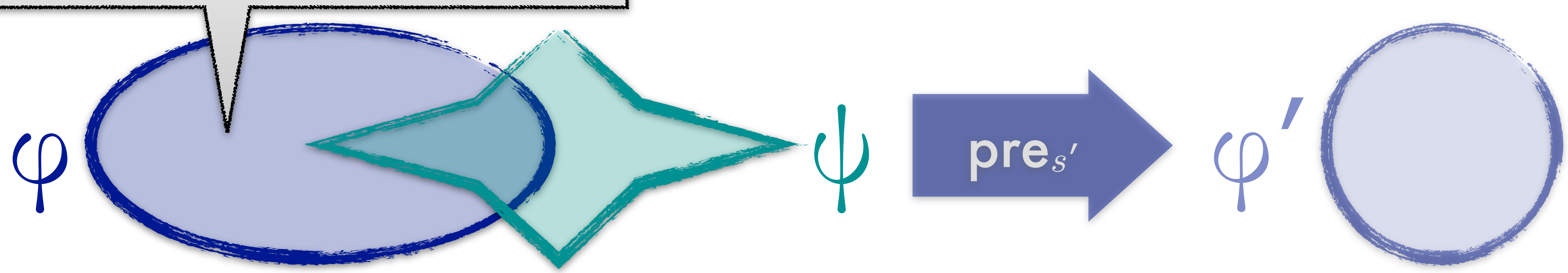

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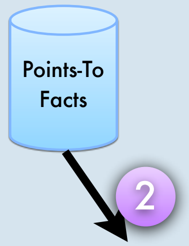

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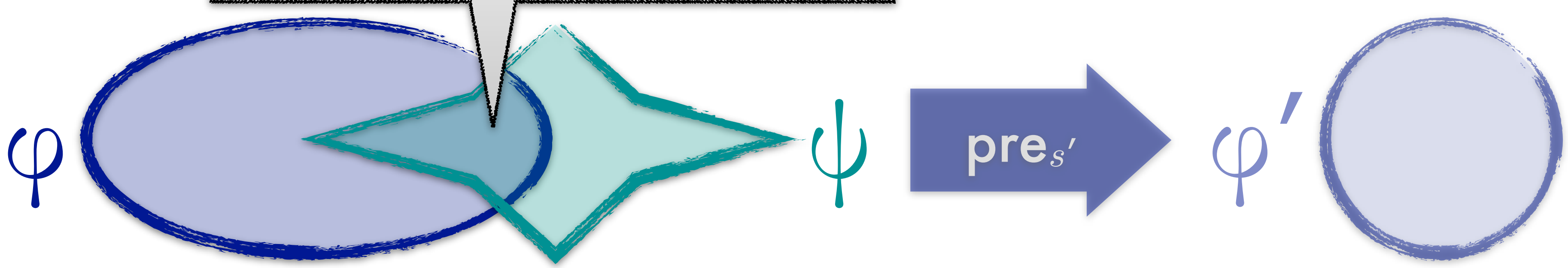
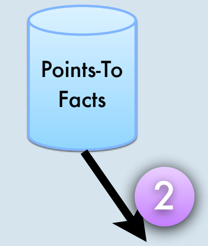


Leverage first analysis by designing **specialized** constraint forms



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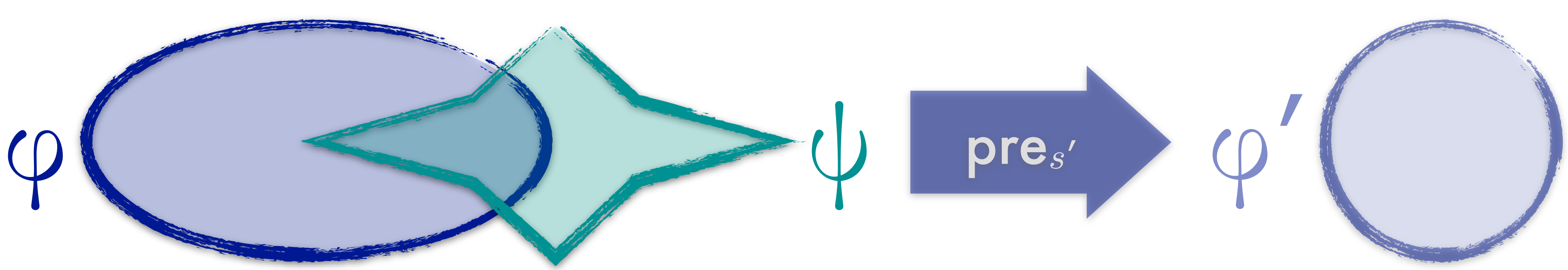

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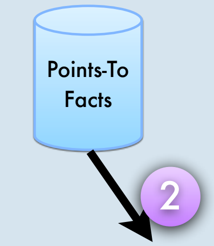

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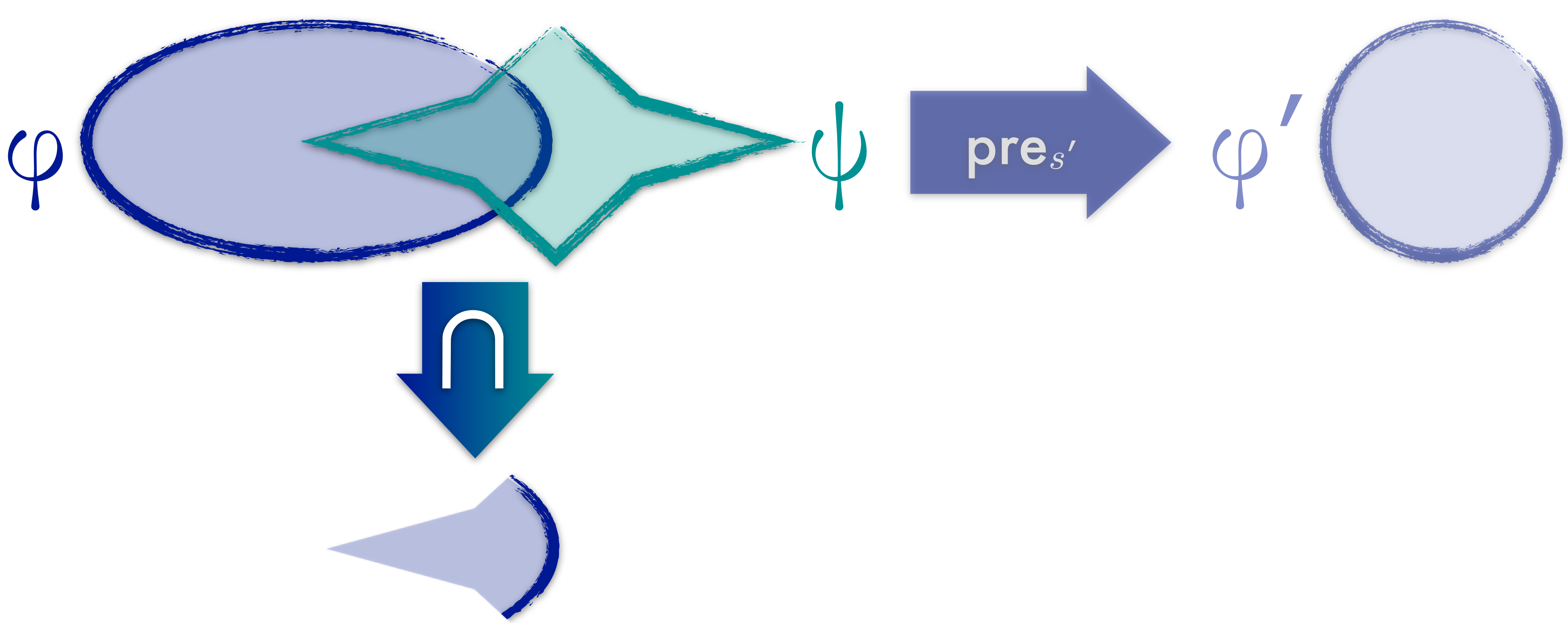

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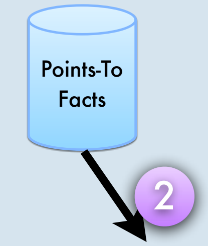

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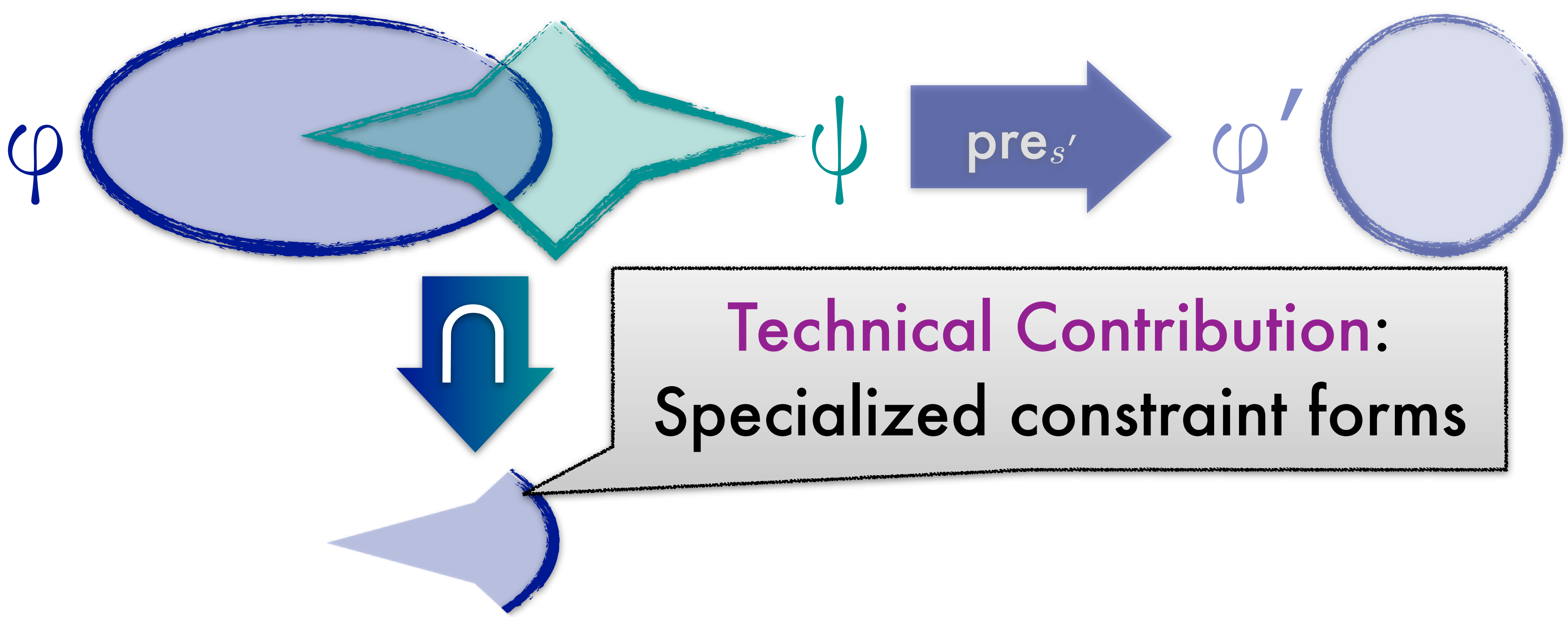

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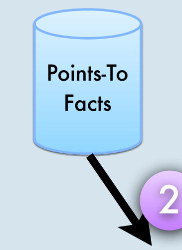

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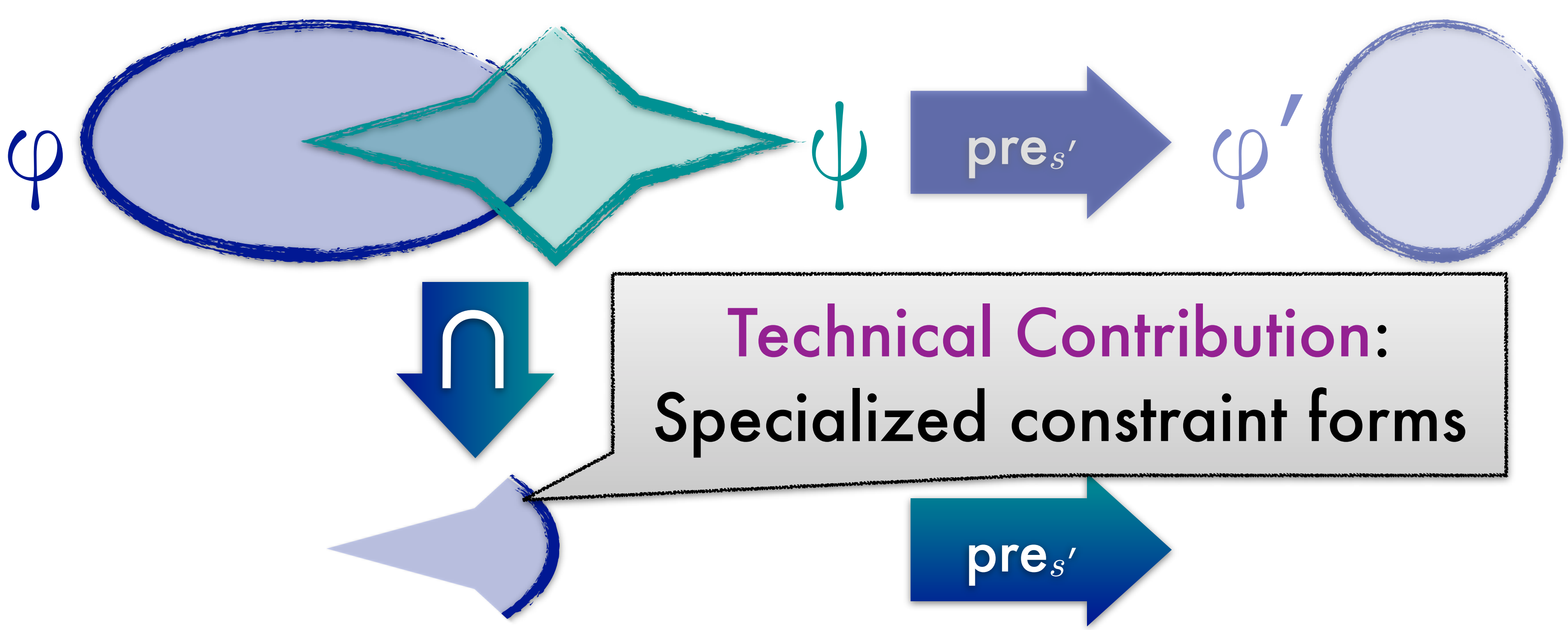

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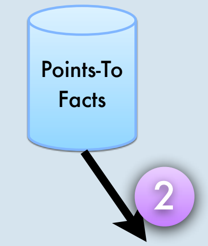

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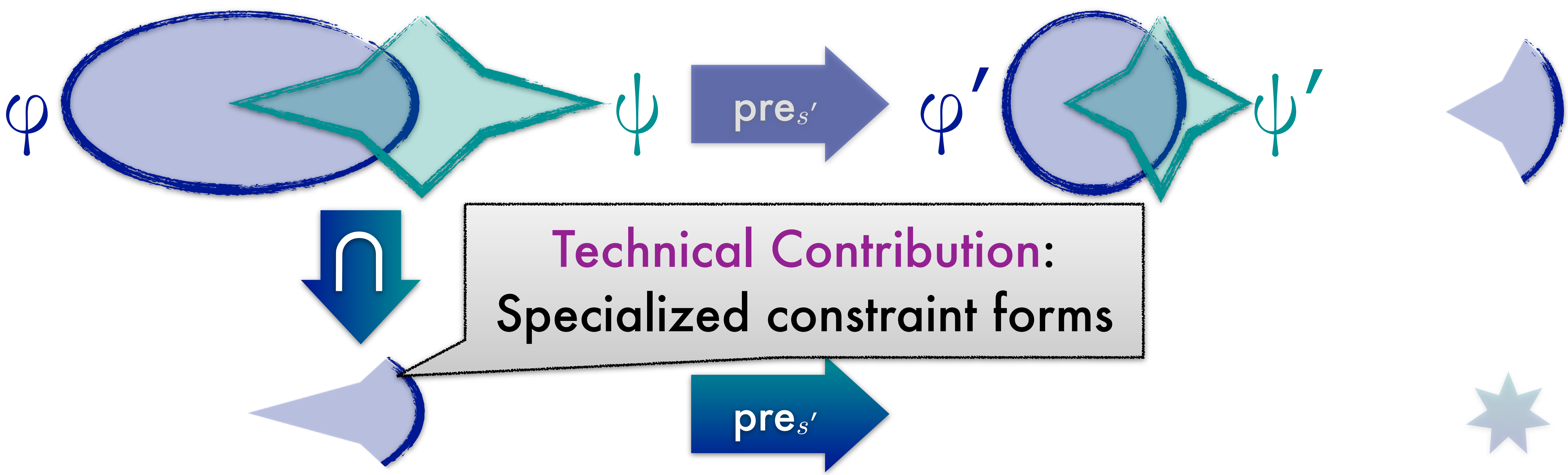

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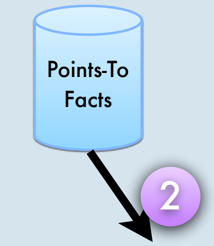

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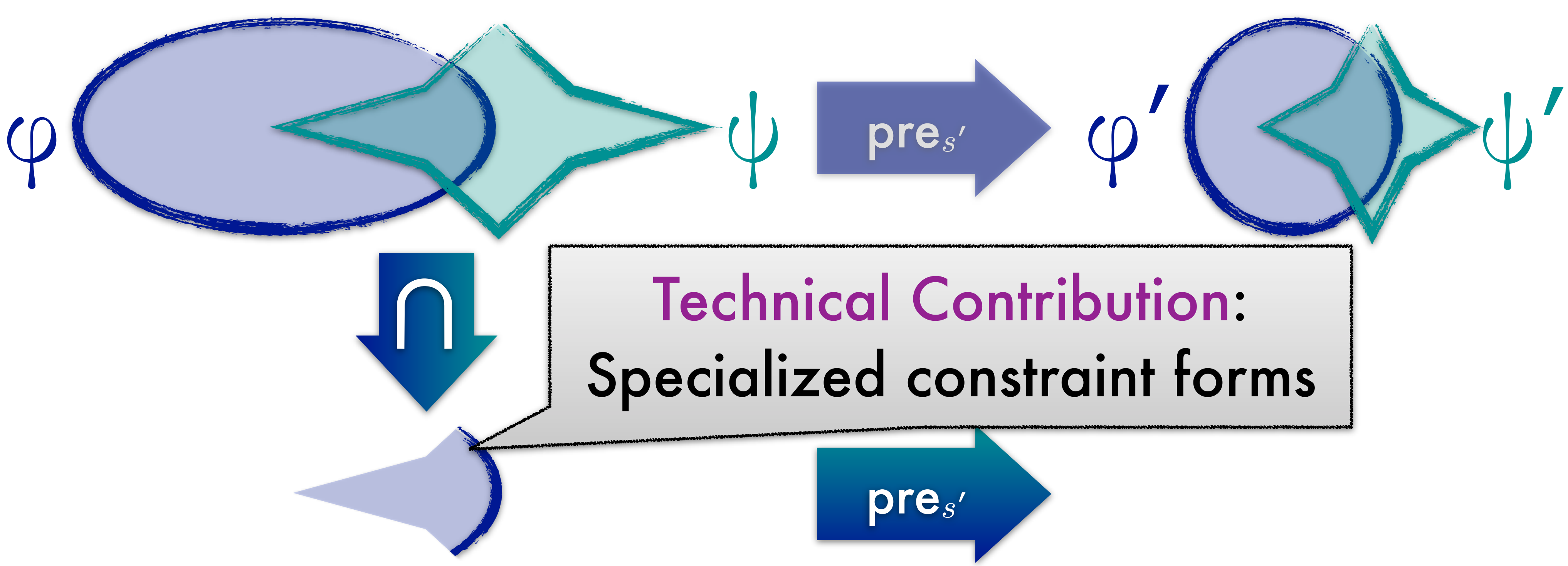

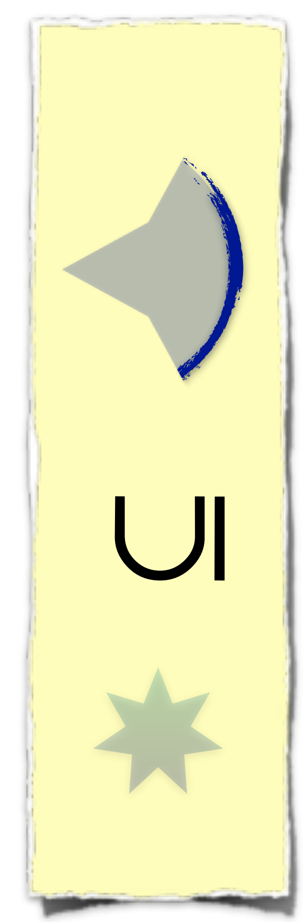

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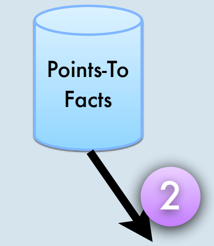

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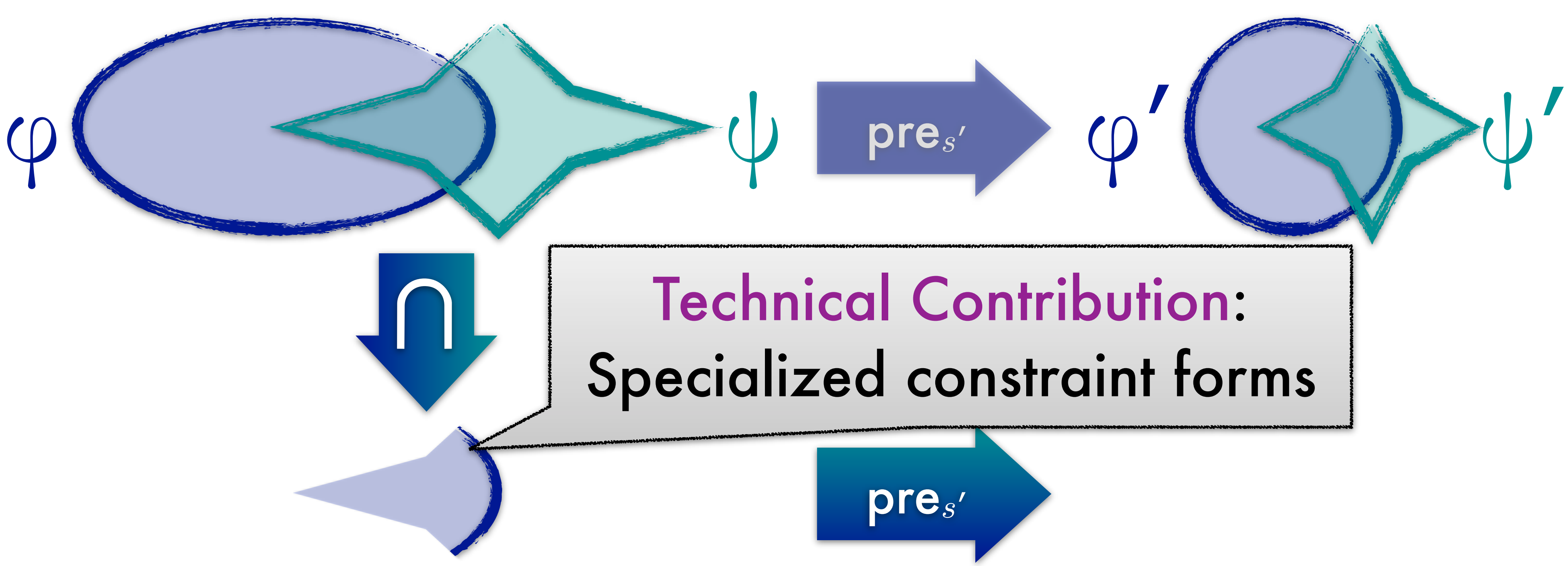
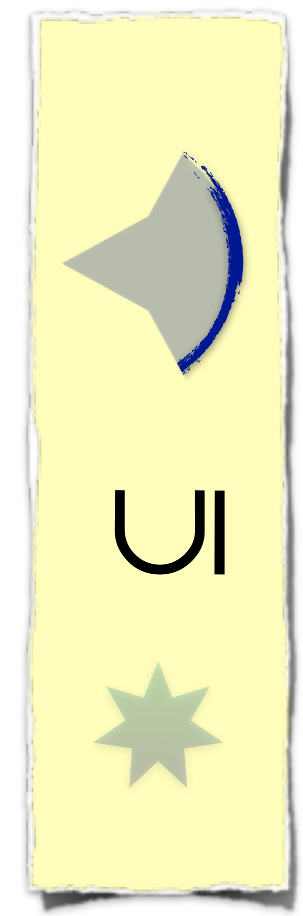
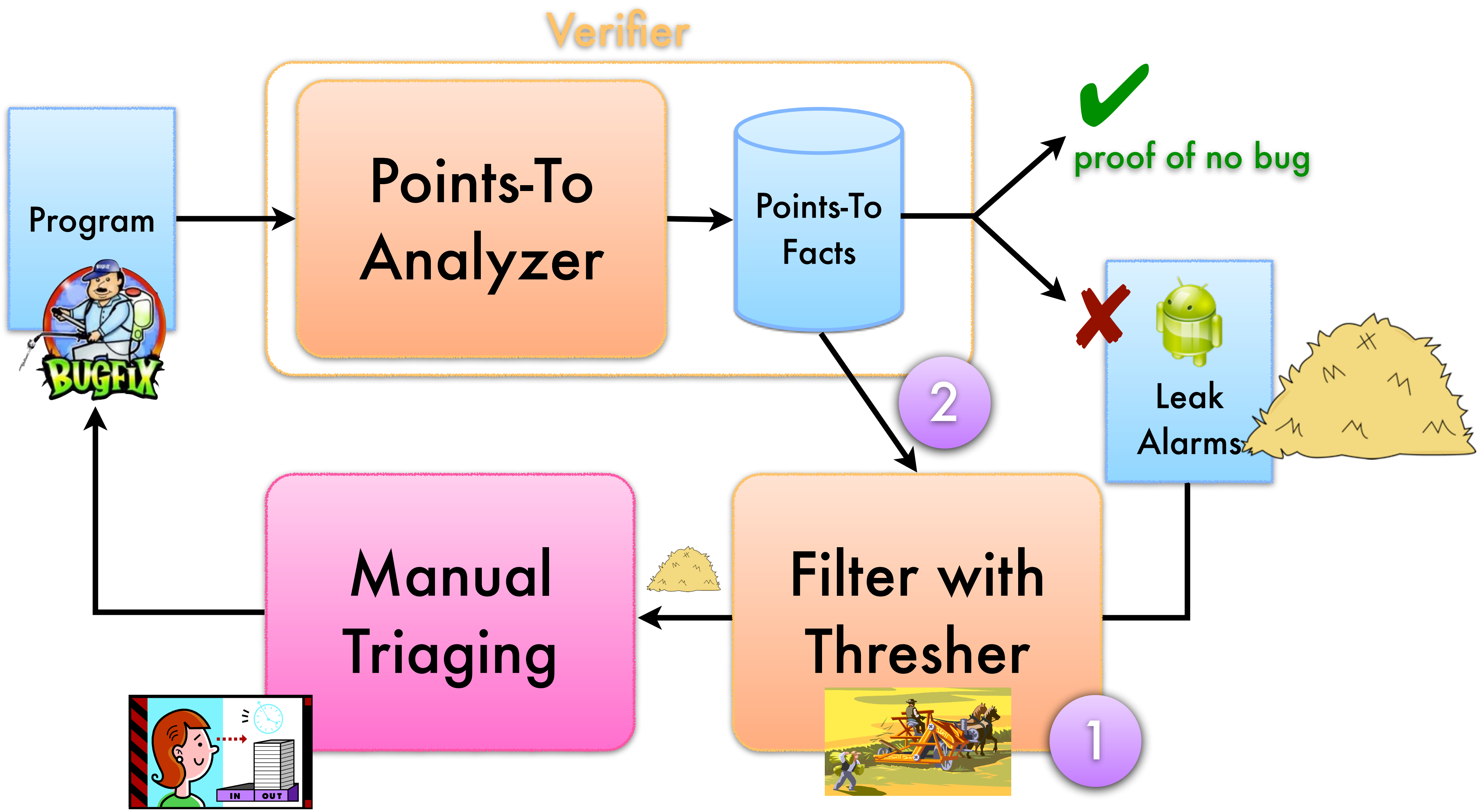
Specialized constraint forms makes finding refutations feasible





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

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
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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triage "well" at ~1–2 hours per alarm

`staticfield-Activity` pairs

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`staticfield-Activity` pairs

Filtered

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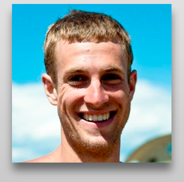
`staticfield-Activity` pairs

Filtered

Manual



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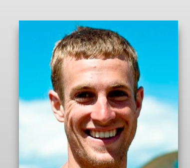
triage "well" at 10–15 minutes per

`staticfield`-`Activity` pairs

Filtered

Manual



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< ~coffee to lunch break

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StandupTimer	2K	25	15	0	1068
DroidLife	3K	3	0	3	1
SMSPopUp	7K	5	1	4	46
aMetro	20K	54	18	36	18
K9Mail	40K	208	130	64	374
Total	**72K**	**311**	**172**	**115**	**1602**

Is Thresher effective at 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

Guesstimate

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

Triage "ok" without: ~30 hours

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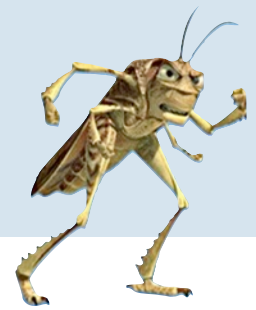
Android OS

... in the process of finding leaks in apps

Find the Android's HashMap bug ...



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class HashMap {
  static Object[] EMPTY = new Object[2]; ...
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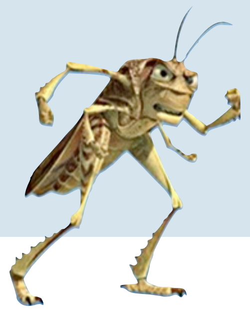

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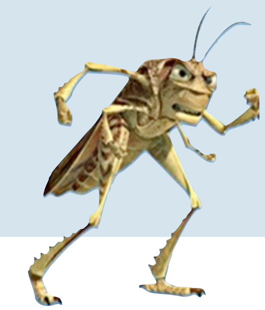

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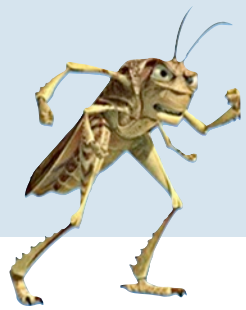

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allocate new backing array on first write

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Text

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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Text

return 0

return "evil" content

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

Find the Android's HashMap bug …

```
cla
  s
  H

  v

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```

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

Text

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

Text

We reported this, Google fixed it

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

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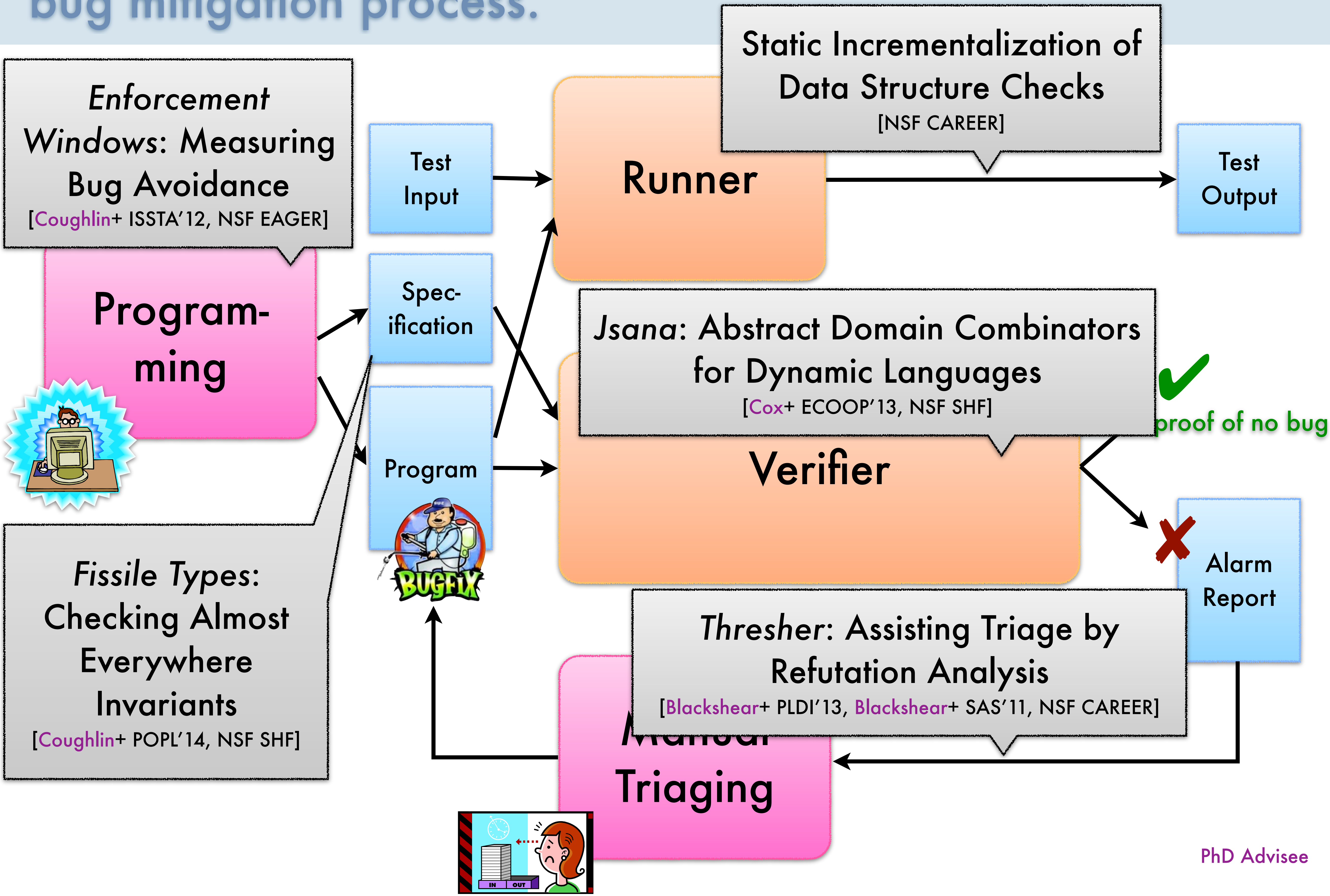
Contribution: Addressed the false alarm problem with

a “smart and precise filter”

a refutation analysis

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



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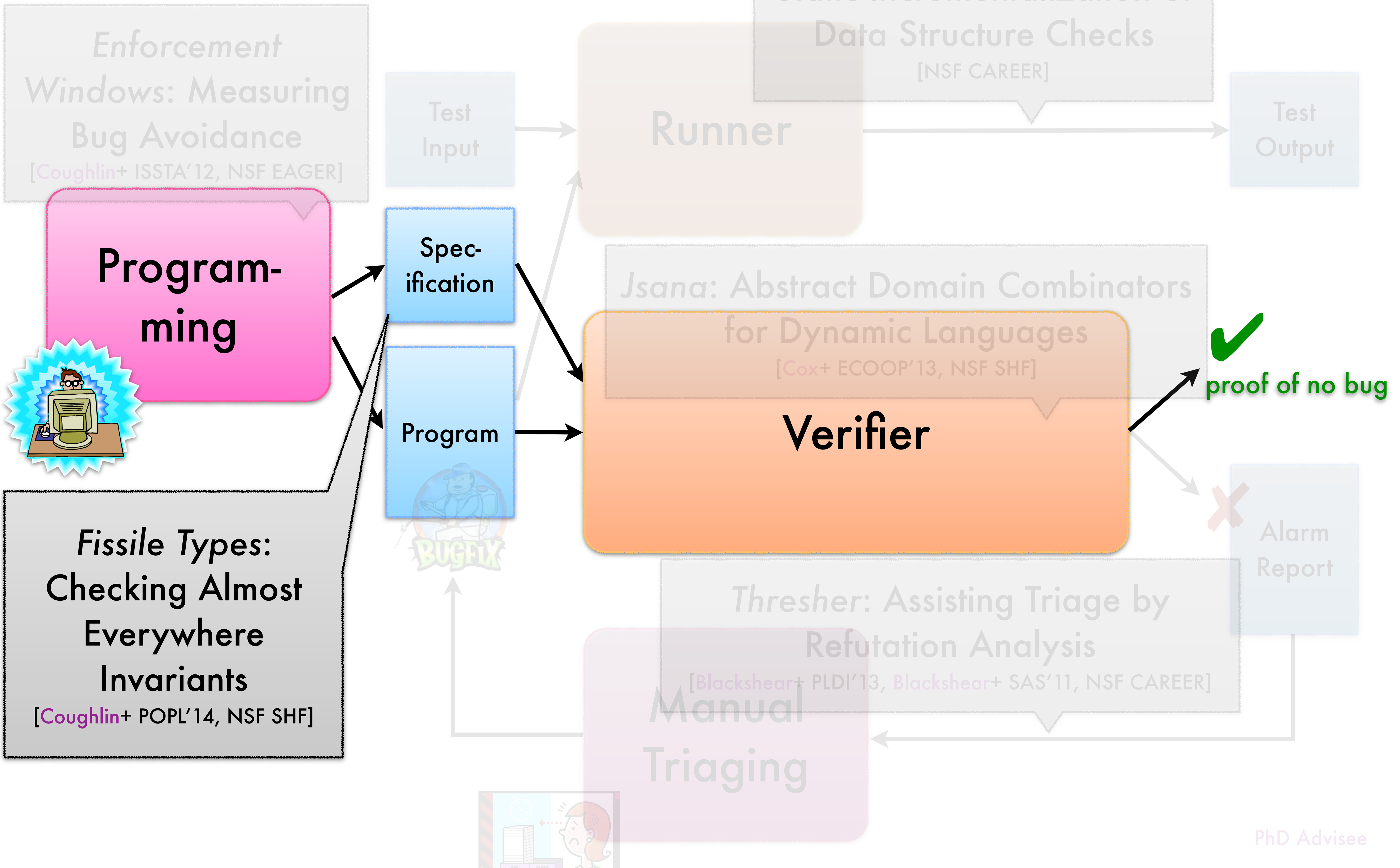

Fissile Types: Checking Reflection with Almost Everywhere Invariants

Method Reflection and the Great Divide

Method Reflection and the Great Divide

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

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type system designers

“web 2.0” developers

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Type system designers **worry**.

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

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`object[string]()`

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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]()
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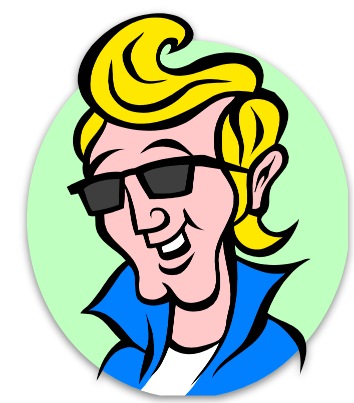
type system designers

"web 2.0" developers



Type system designers **worry**.

Wh

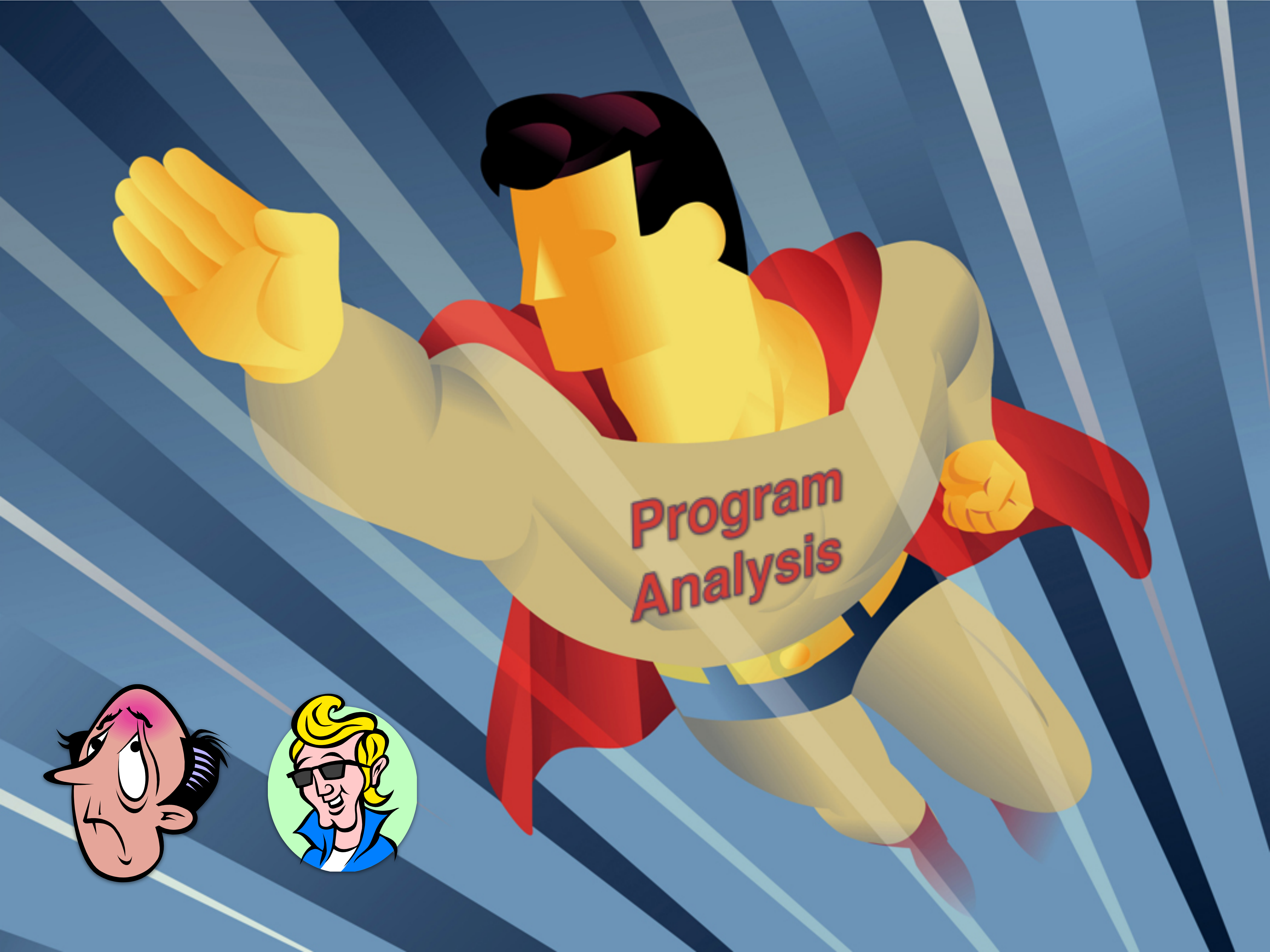
obj

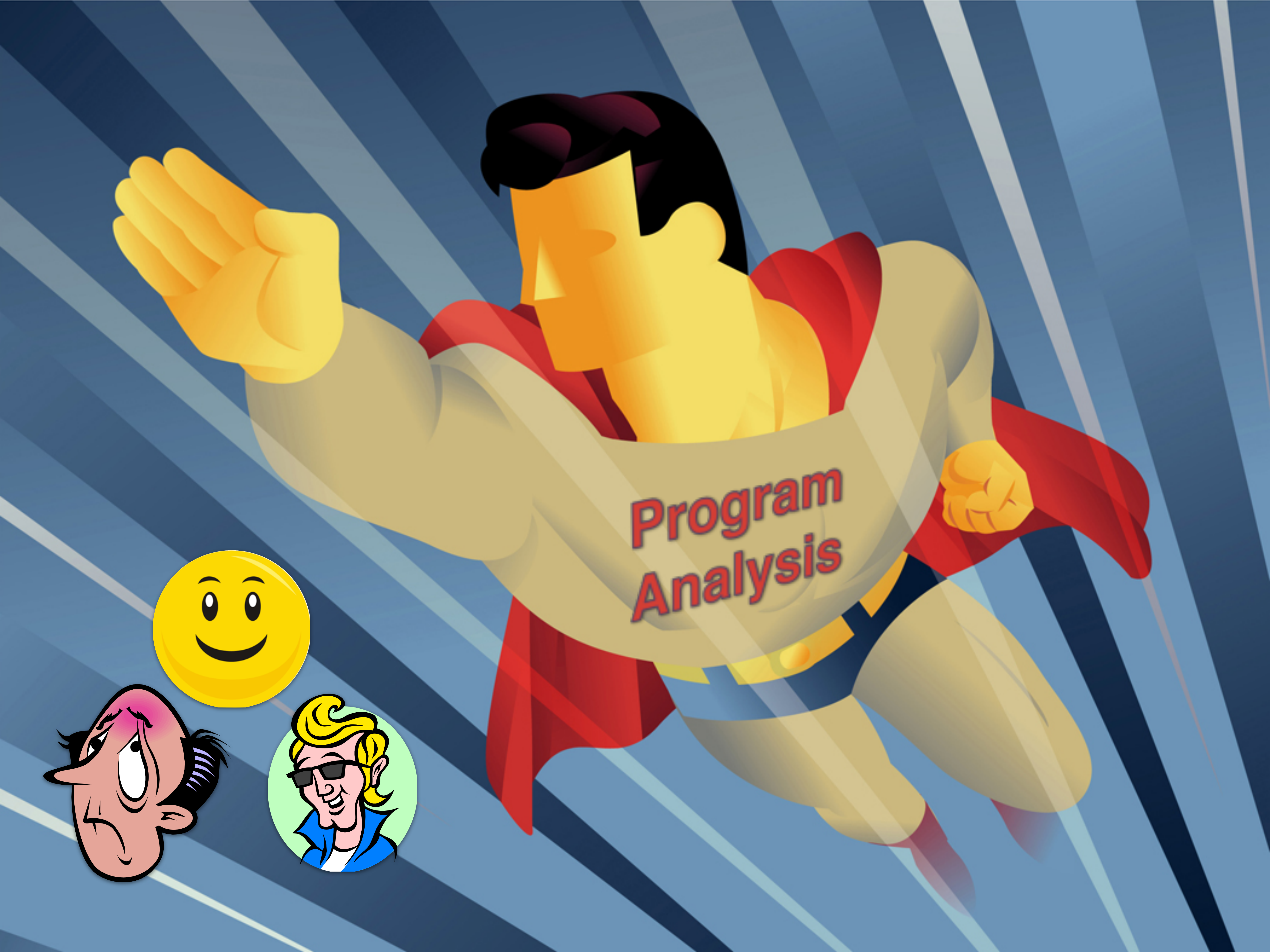
by

"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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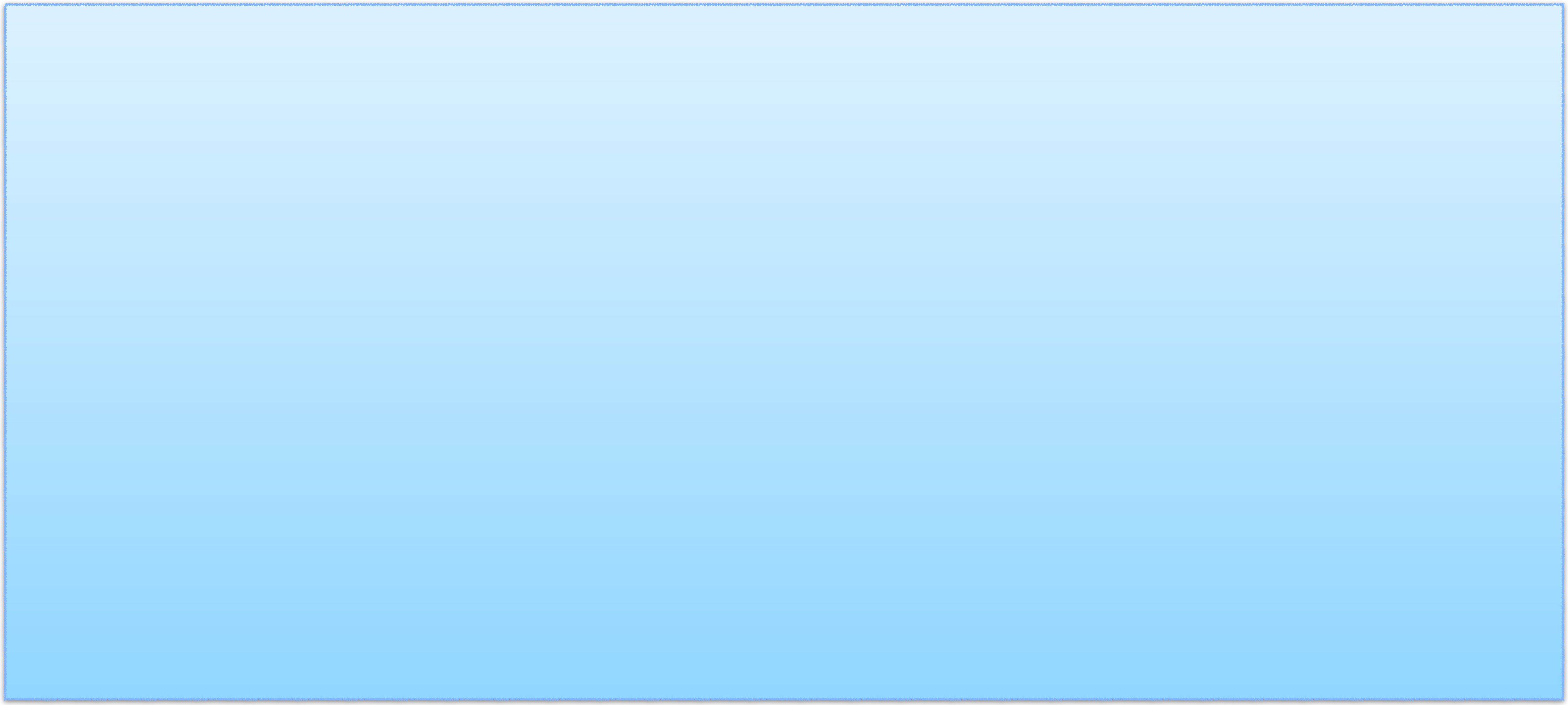

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callback.o[callback.m]()
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Program

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

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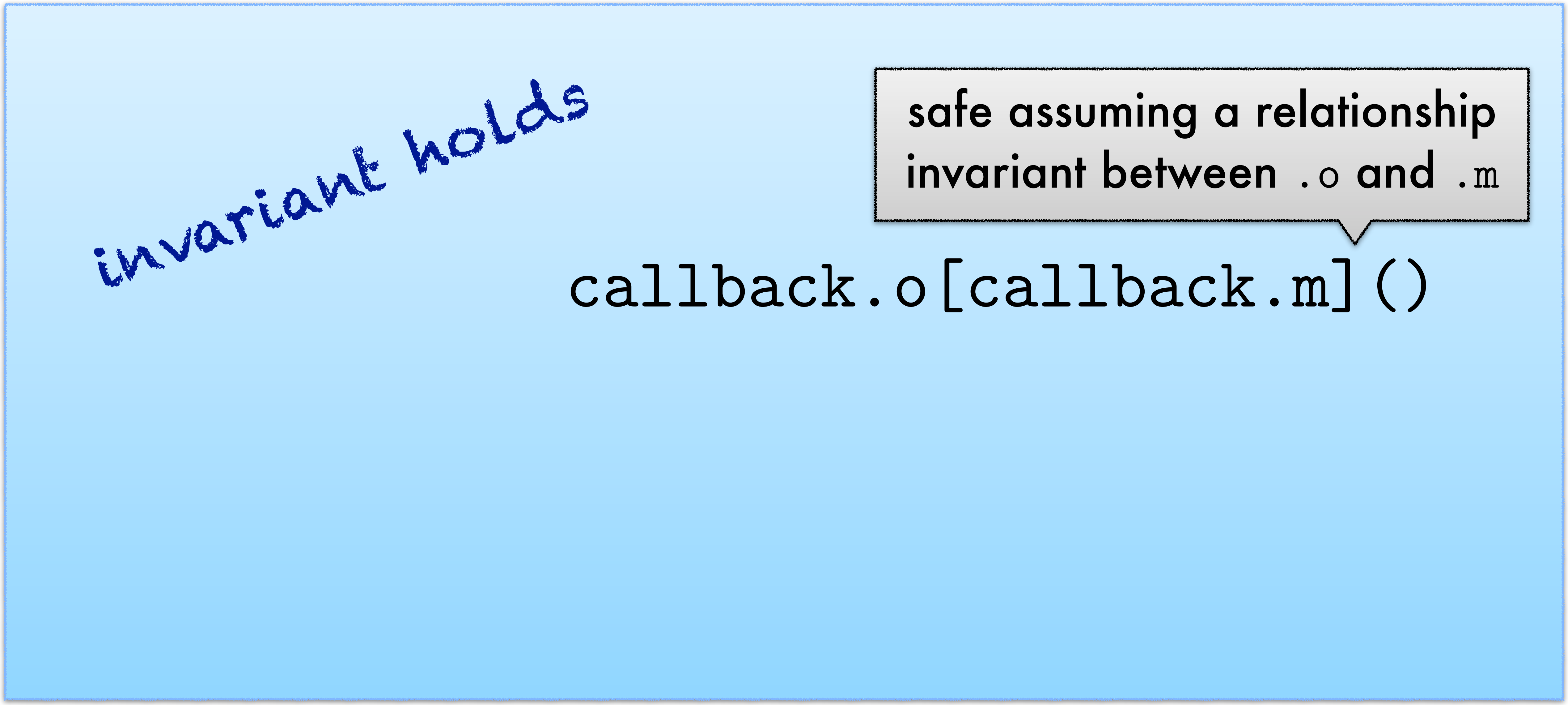

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invariant broken

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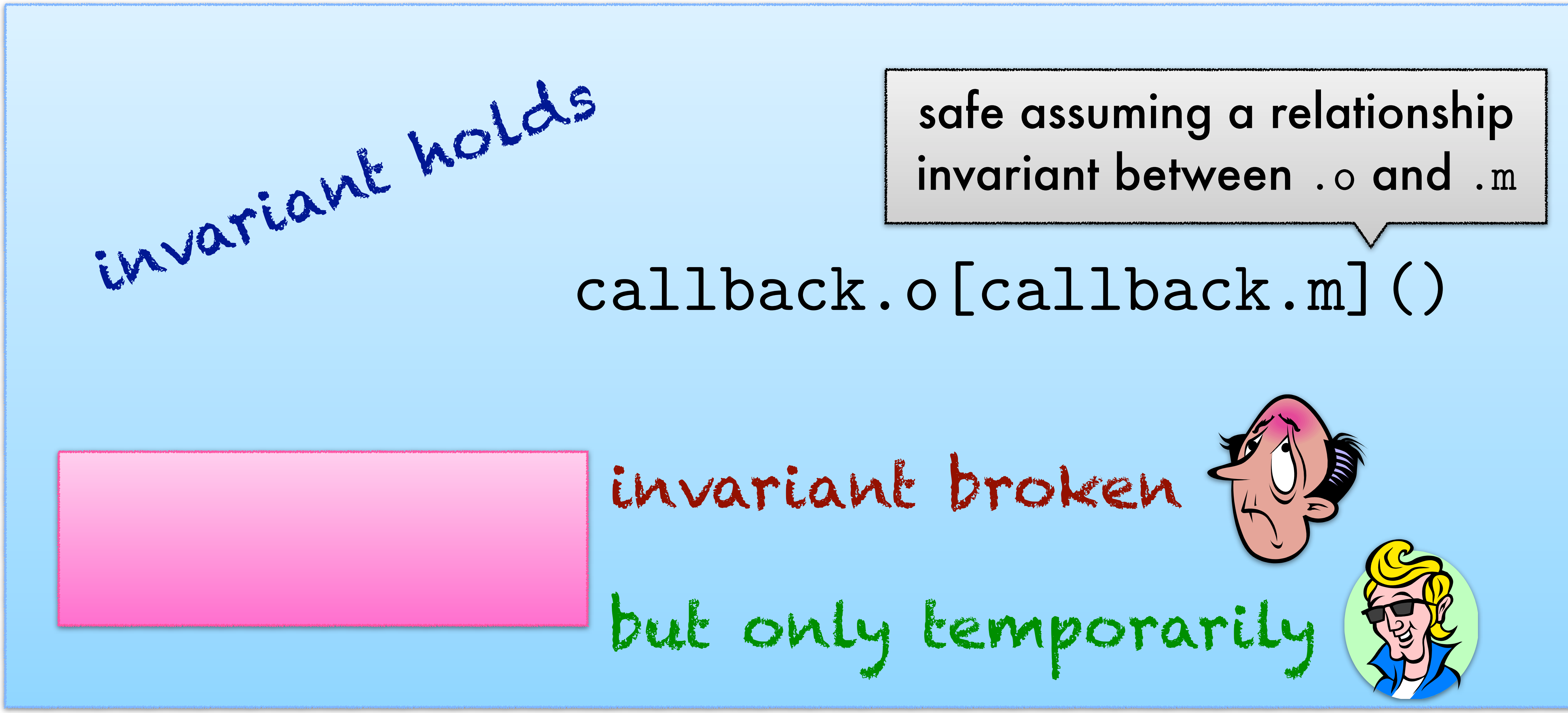

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invariant broken

but only temporarily

Program

Tolerate "temporary" violation with 

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inva

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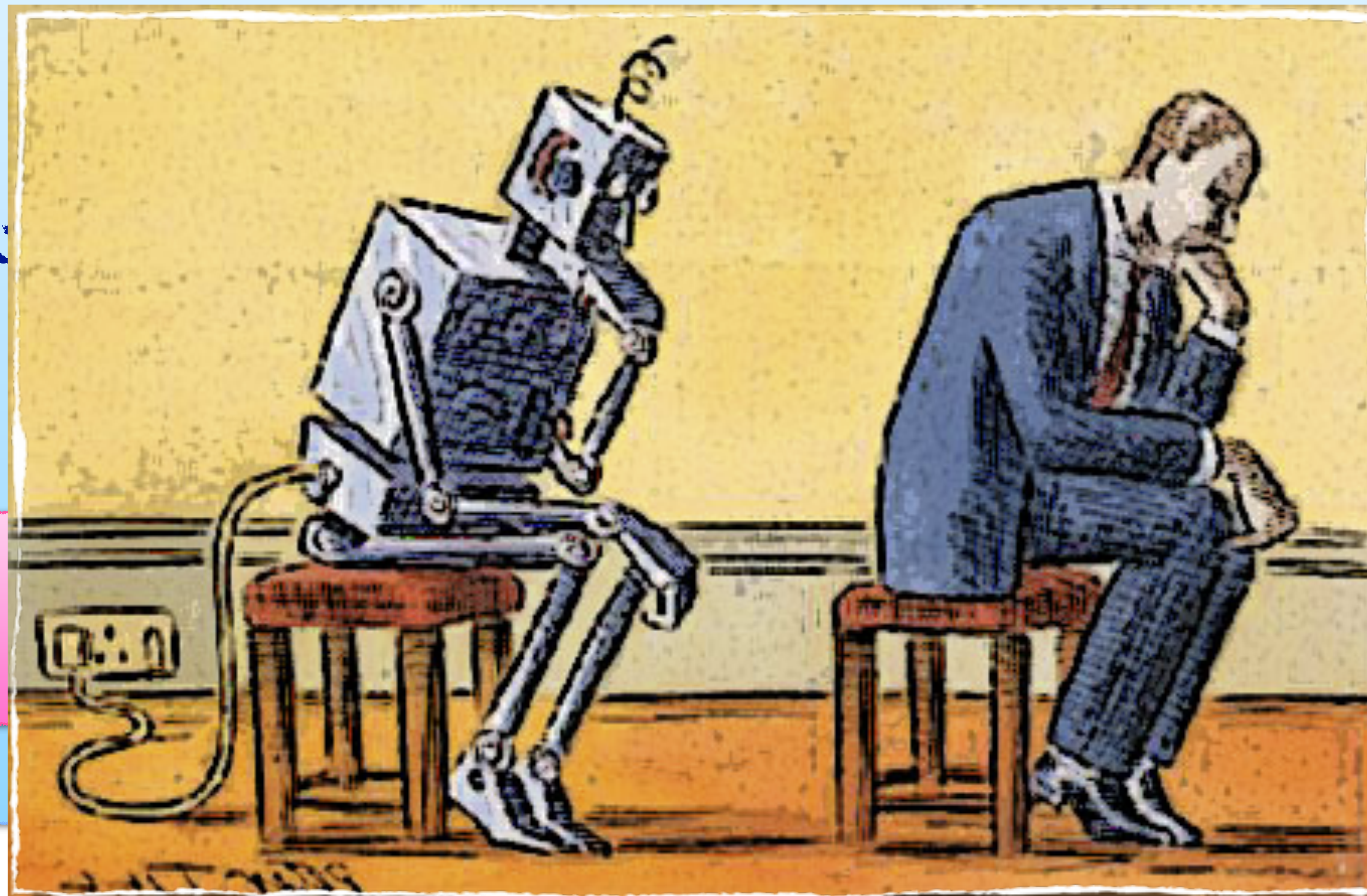
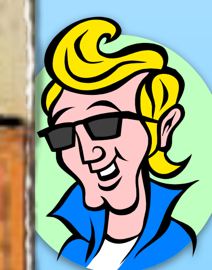
] ()





Tolerate “temporary” violation with 

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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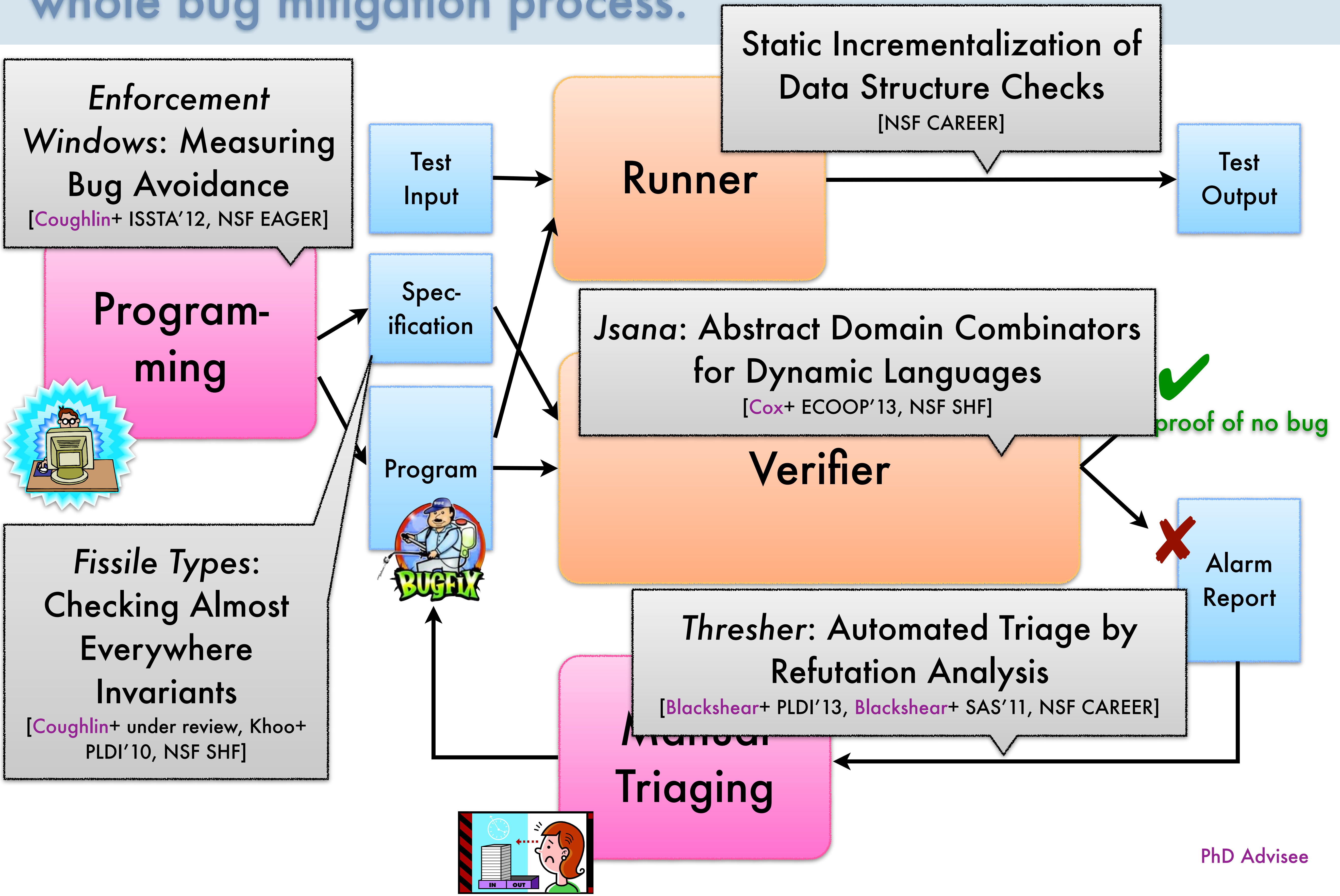
Big Deal: makes IDE integration possible

Summary: The cooperative approach addresses the whole bug mitigation process.



Future Directions

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The Cooperative Approach

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- Evidence for Alarms: alarm explanations, probability of bug
- Hardening: synthesize efficient dynamic checks
- Patch Synthesis: synthesize bug fixes
- Performance and Scalability Bugs: beyond correctness bugs
- Input Debugging: bugs in input
- Analysis Engines: in new software domains

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Software Domains

- Dynamic: web, science+engineering
- Concurrent: event-driven systems, user-interactive systems, servers
- Distributed: "big data" software

Acknowledgments

NSF

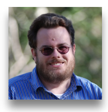
NREL

National Renewable Energy Laboratory

Acknowledgments

PhD Advisees

Sam Blackshear 

Devin Coughlin 

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Yi-Fan Tsai 

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Alex Beal (BS)

Kira Quan (BS)

Chris Bubernak (BS)

James Holley (BS)

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Tom Yeh

Rick Han

Eric Keller

Dirk Grunwald

John Black

Amer Diwan (Google)

Jeremy Siek (Indiana)

Manu Sridharan (IBM Research)

Xavier Rival (INRIA/ENS Paris)

Jeff Foster (Maryland)

Atif Memon (Maryland)

Cesar Sanchez (IMDEA)

PLV

“Nothing so needs reforming as other people’s habits.” – Mark Twain

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Criticize with care and empathy not condemnation

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"cooperative program analysis principle and challenge"

PLV

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