



# Cooperative Program Analysis

**Bor-Yuh Evan Chang**  
University of Colorado Boulder

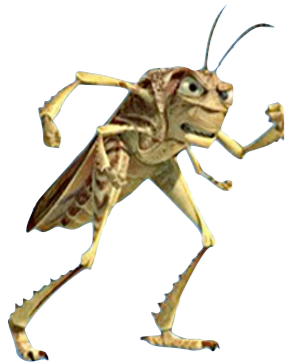


National Taiwan University 國立臺灣大學  
August 5, 2014





# A program analysis story ...







**Software is everywhere and varying more and more**



traditional



Software is everywhere and varying more and more



traditional



mobile



Software is everywhere and varying more and more



traditional



mobile



cloud



Software is everywhere and varying more and more



traditional



mobile



cloud



cyberphysical

Software is everywhere and varying more and more





traditional



mobile



cloud



cyberphysical

Software is everywhere and varying more and more

Software is getting more and more complex



traditional



mobile



cloud



cyberphysical

Software is everywhere and varying more and more

Software is getting more and more complex





**1980s: Bug in Therac-25 kills 6**





**1980s: Bug in Therac-25 kills 6**

**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."**

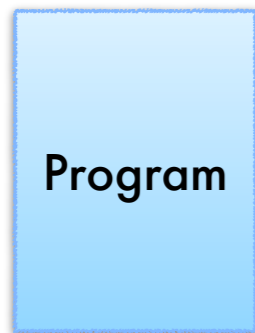




**Program  
Analysis**



## Program Analysis for Formal Verification



**Systematically examine the program to  
“simulate” running it on “all inputs”**





## Program Analysis for Formal Verification



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## Program Analysis for Formal Verification



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**The End?**



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## Program Analysis for Formal Verification

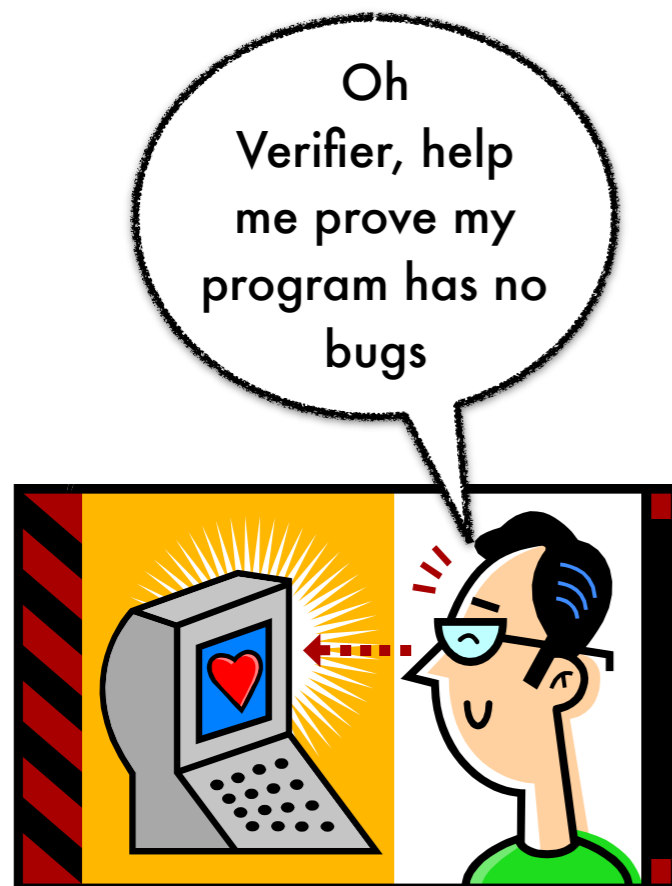


Undecidability necessitates the possibility of **false alarms**. We hope not too many.

# Uncooperative Program Analysis?

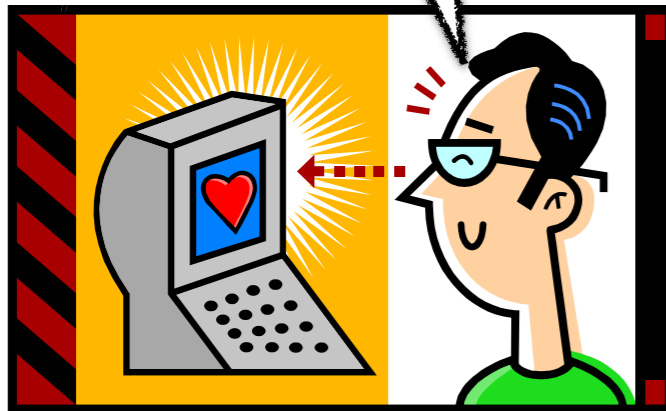


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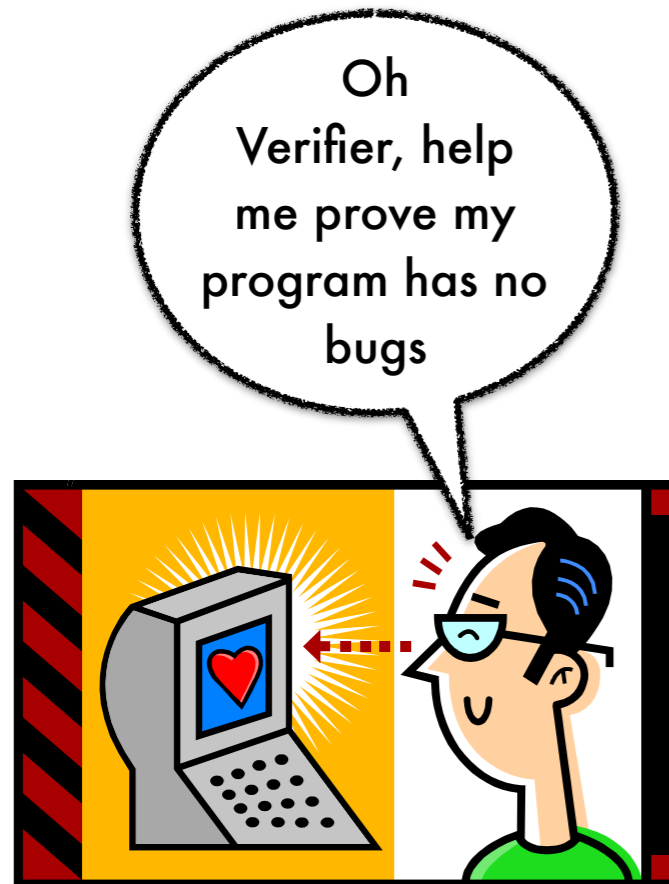
Oh  
Verifier, help  
me prove my  
program has no  
bugs



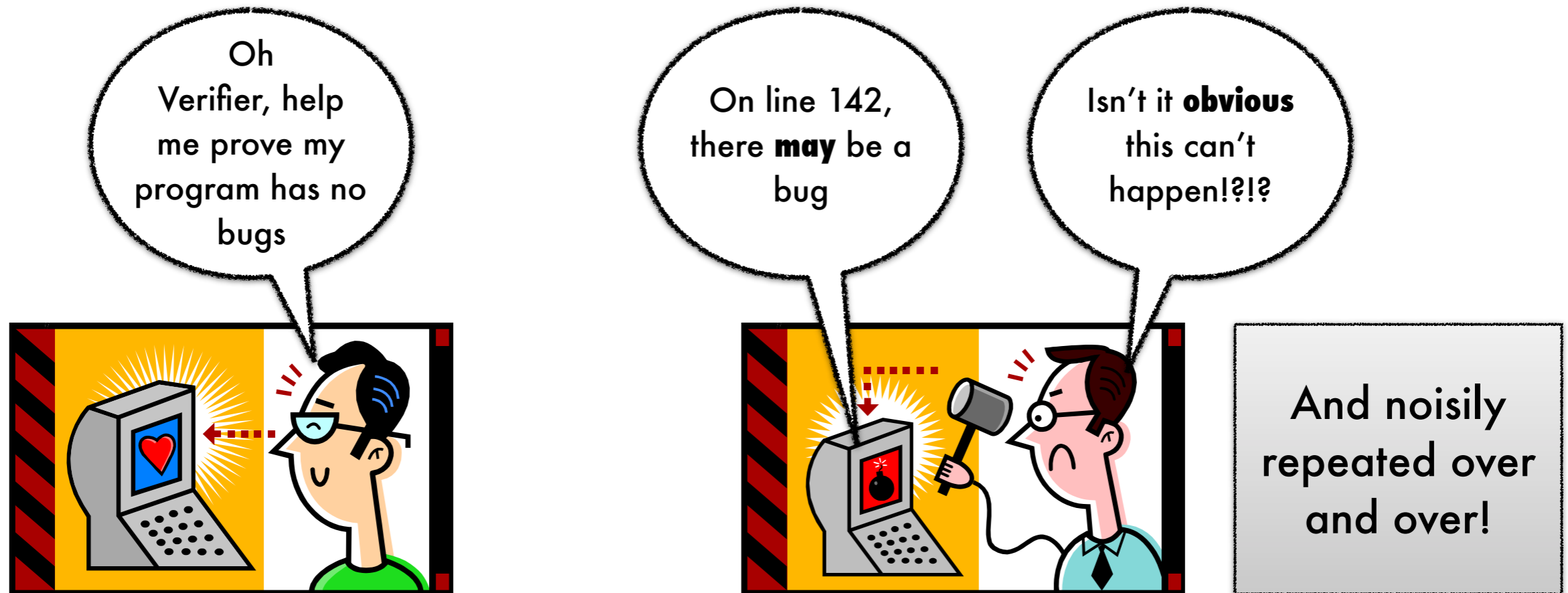
On line 142,  
there **may** be a  
bug



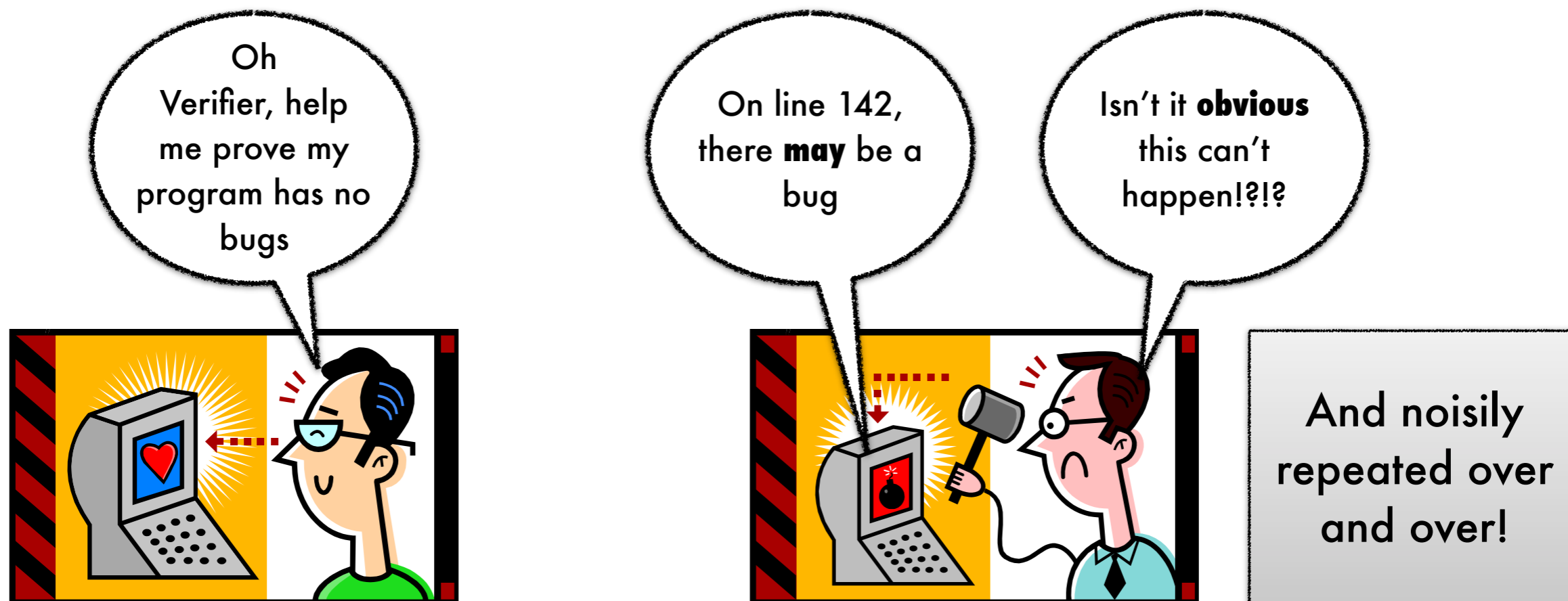
# Uncooperative Program Analysis?



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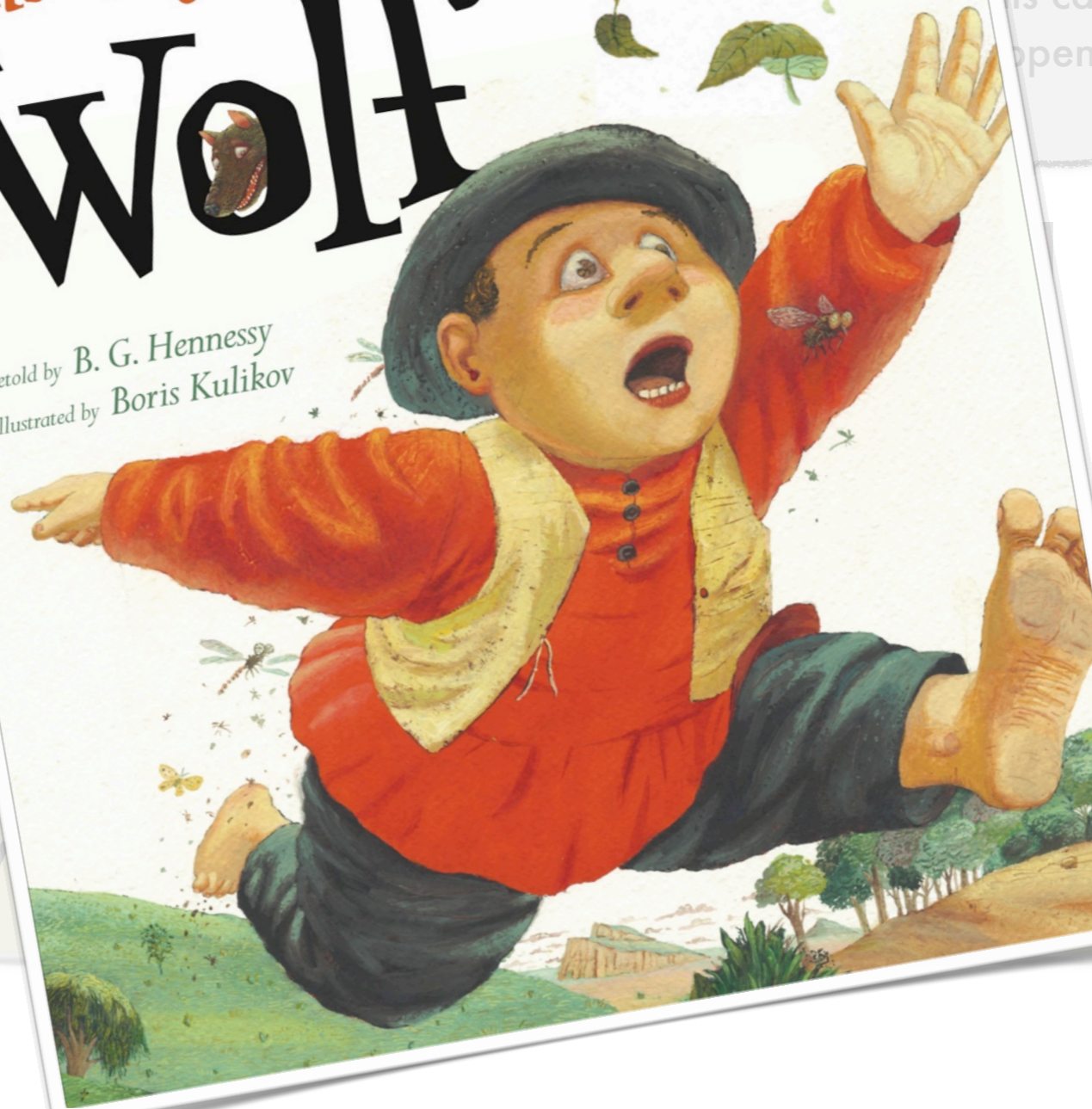
The well-known **false alarm** problem

# Uncooperative Program Analysis?

Oh  
Verified  
me pro  
program  
bug

## The Boy Who Cried Wolf

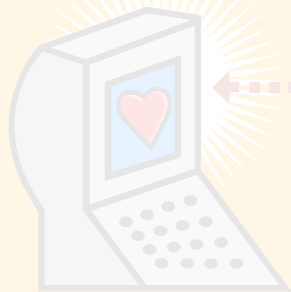
Retold by B. G. Hennessy  
Illustrated by Boris Kulikov



It's obvious  
this can't  
open!?!?

And noisily  
repeated over  
and over!

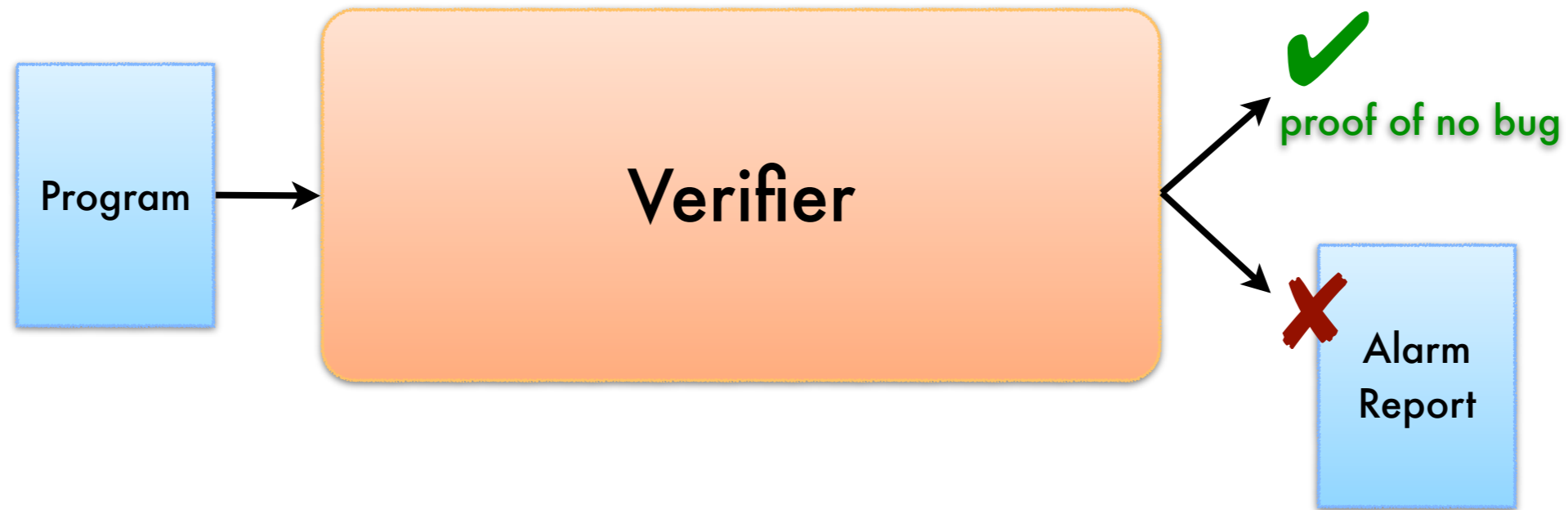
The w



**“[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.”**

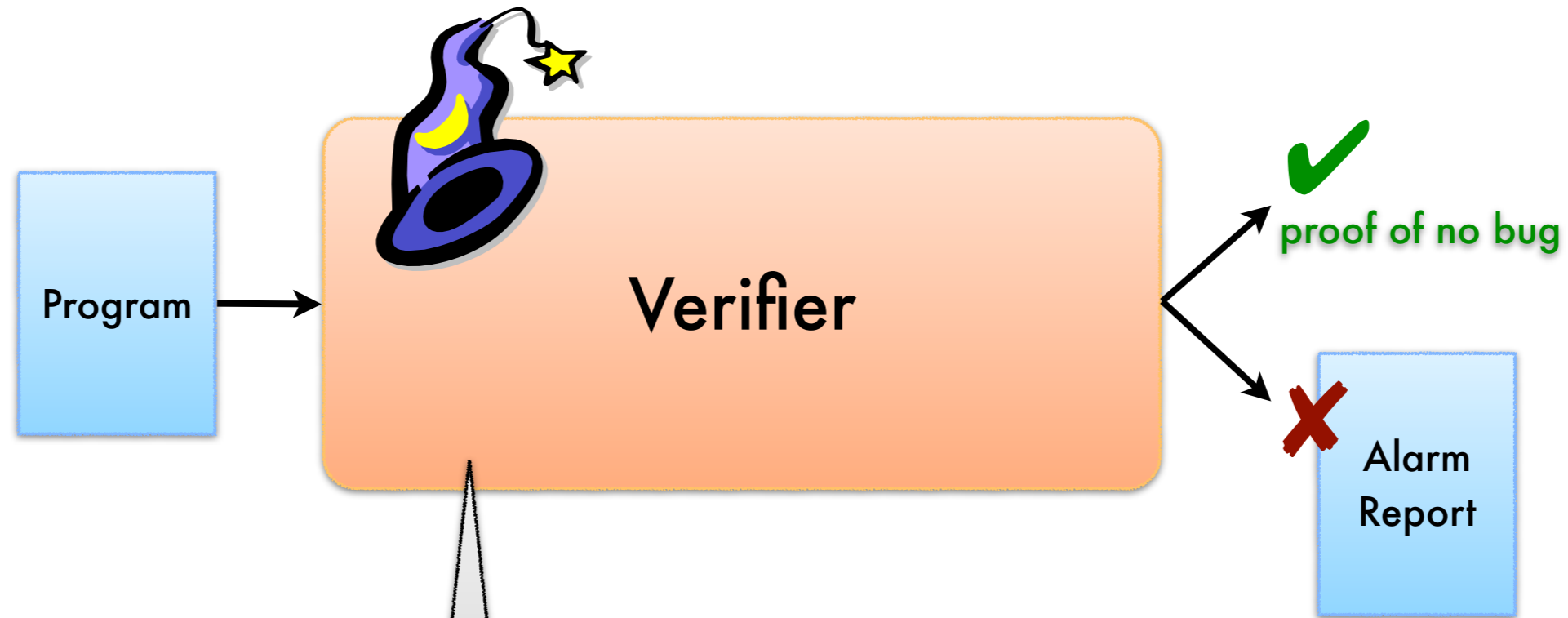
**“A stupid false [alarm] implies the tool is stupid.”**

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



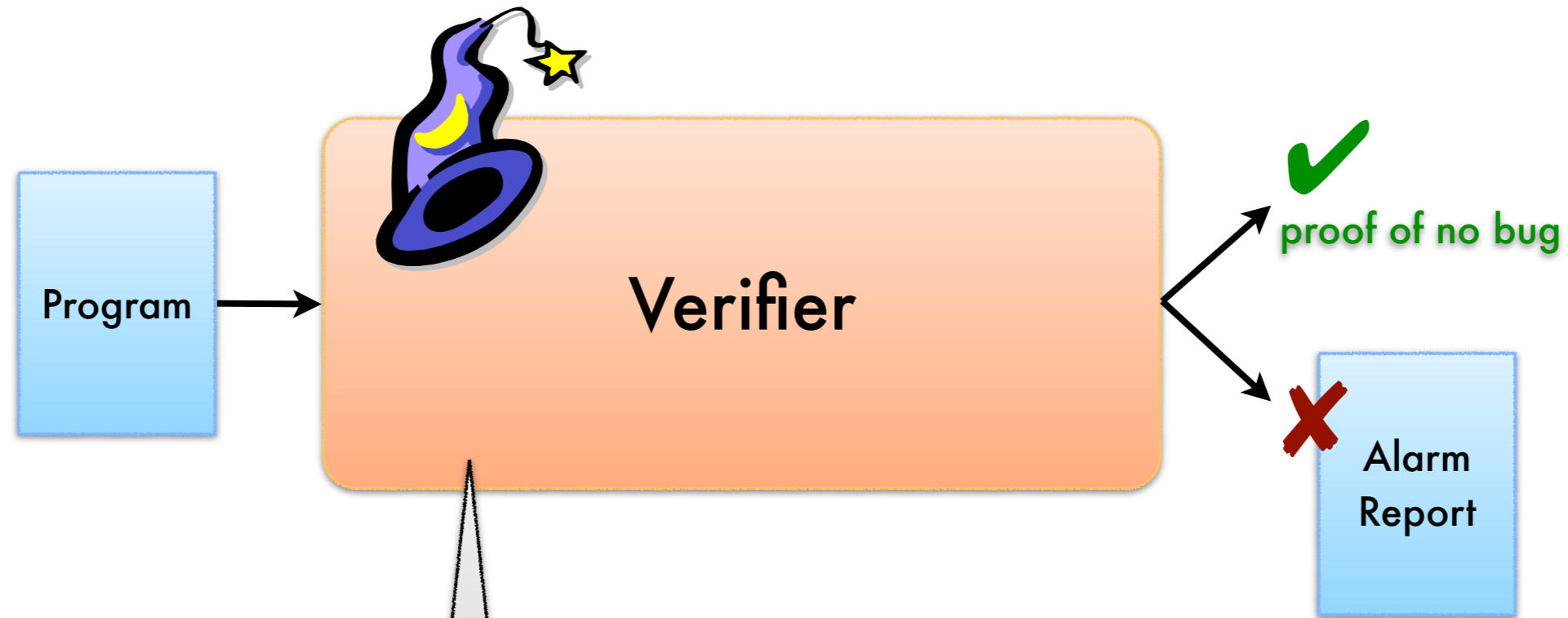


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**Redesign the verifier** with more magic to hopefully reduce the number of false alarms

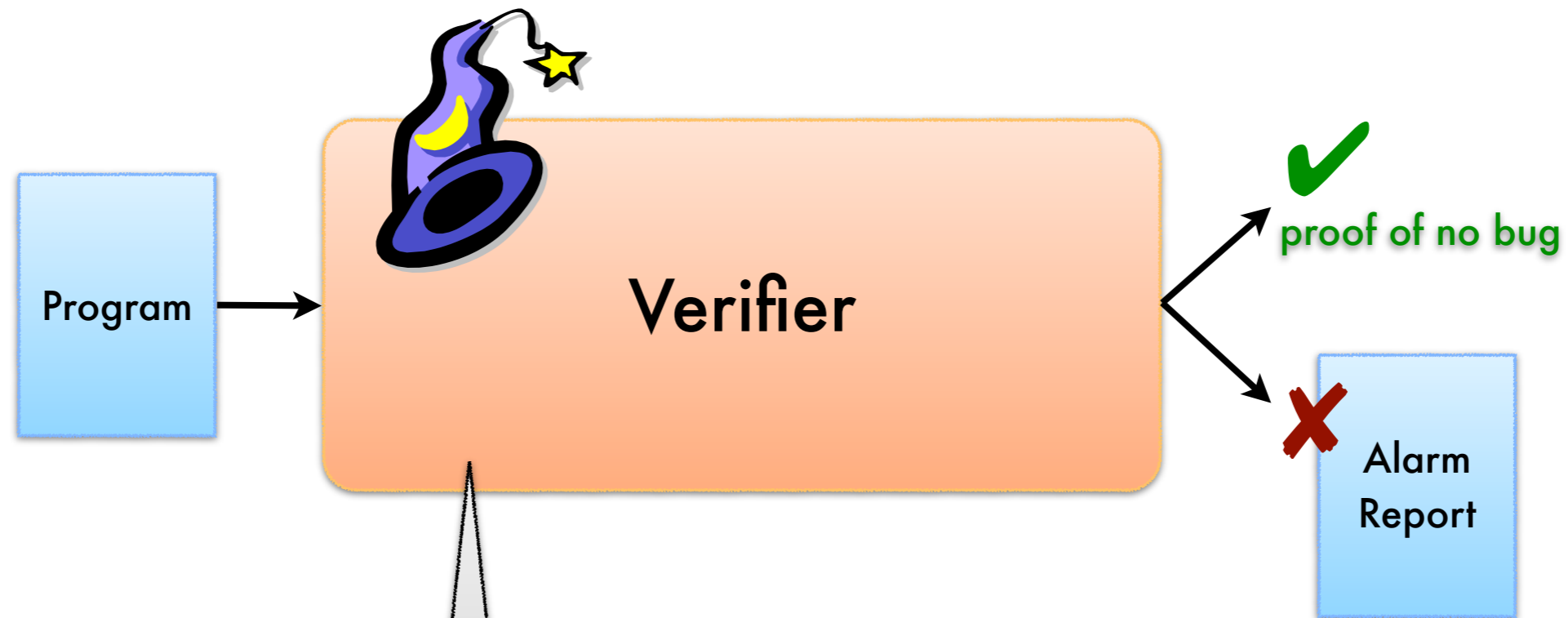
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**But it can never be perfect (undecidability)**

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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"

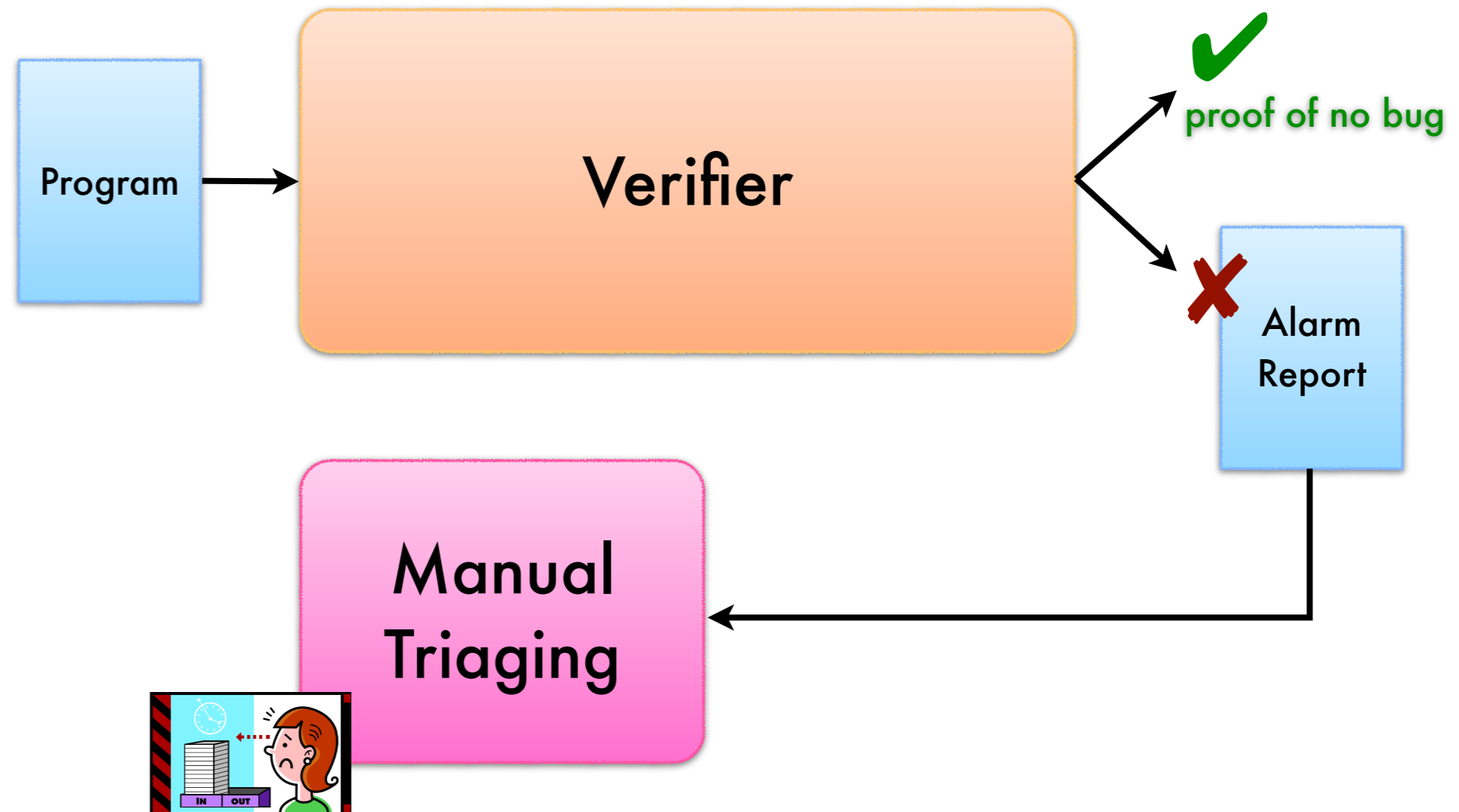
**Agenda:** The cooperative approach addresses the whole bug mitigation process.



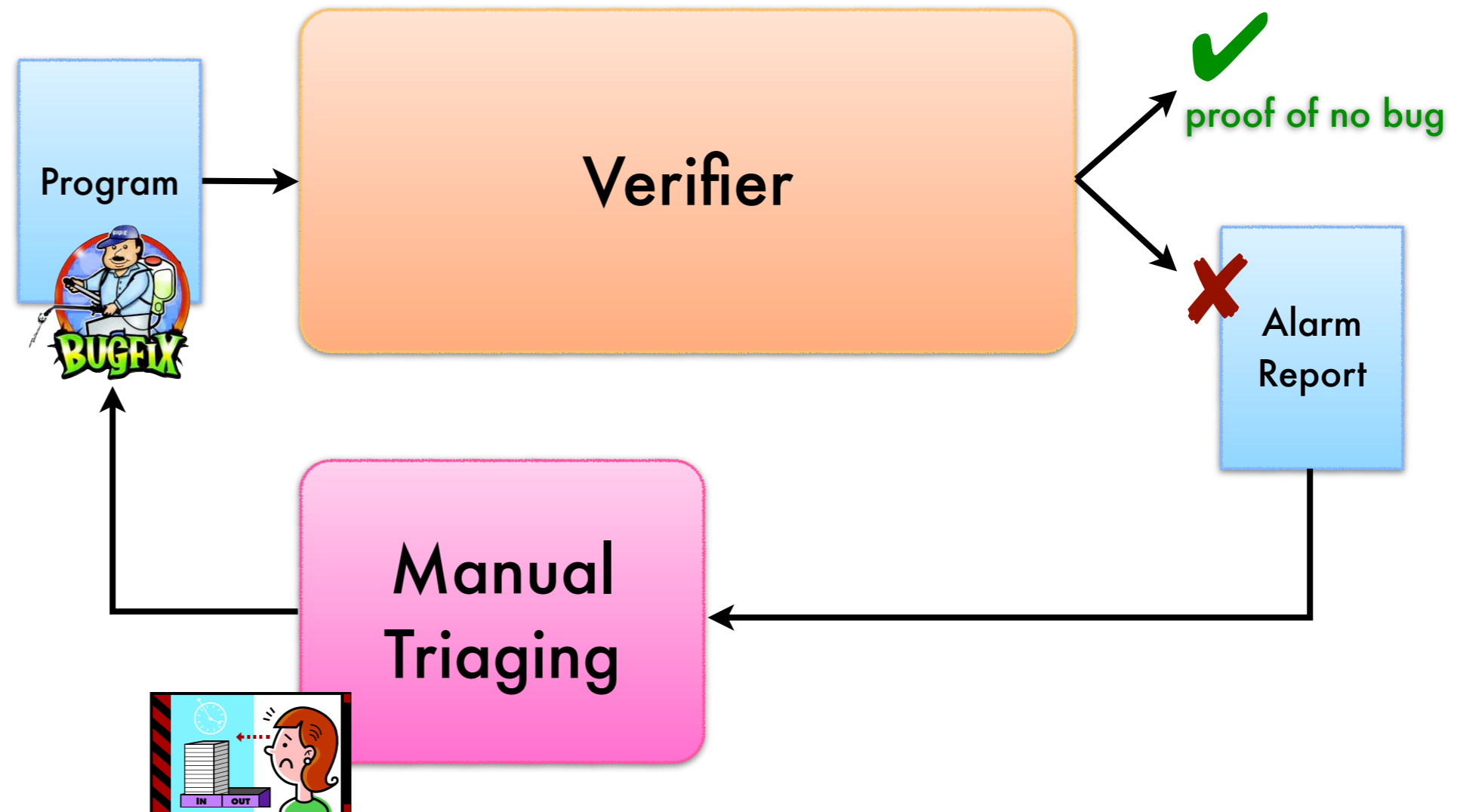
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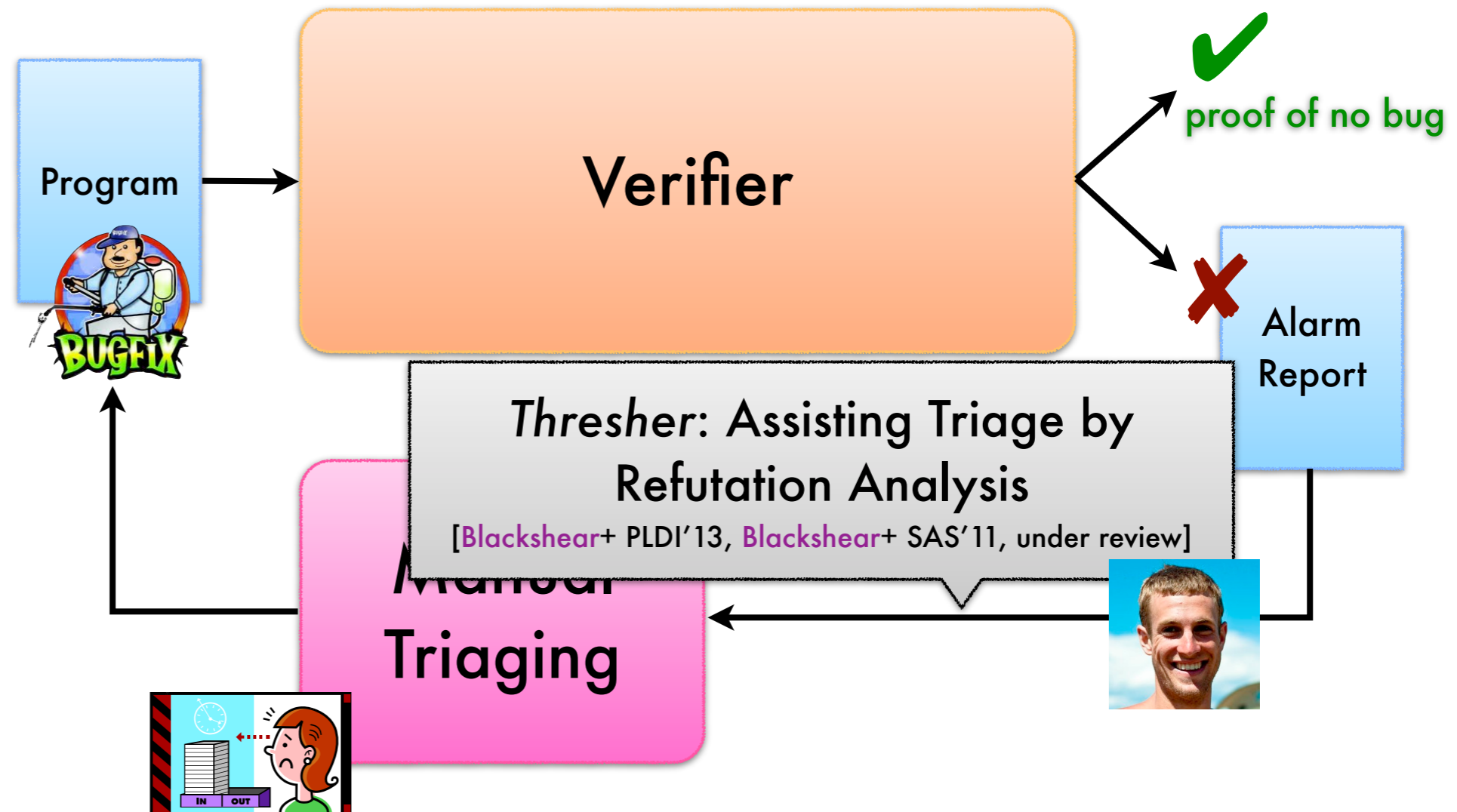
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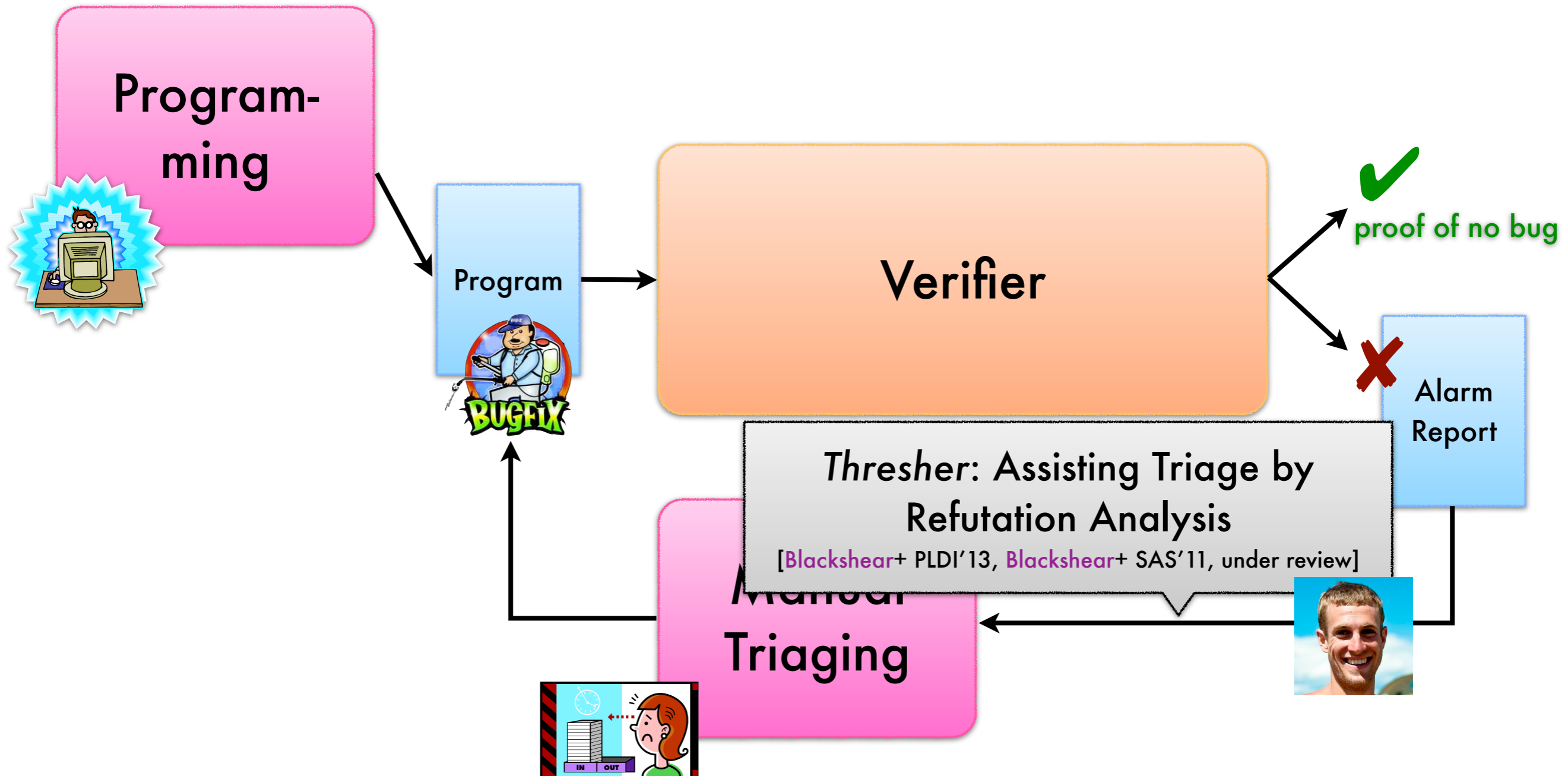


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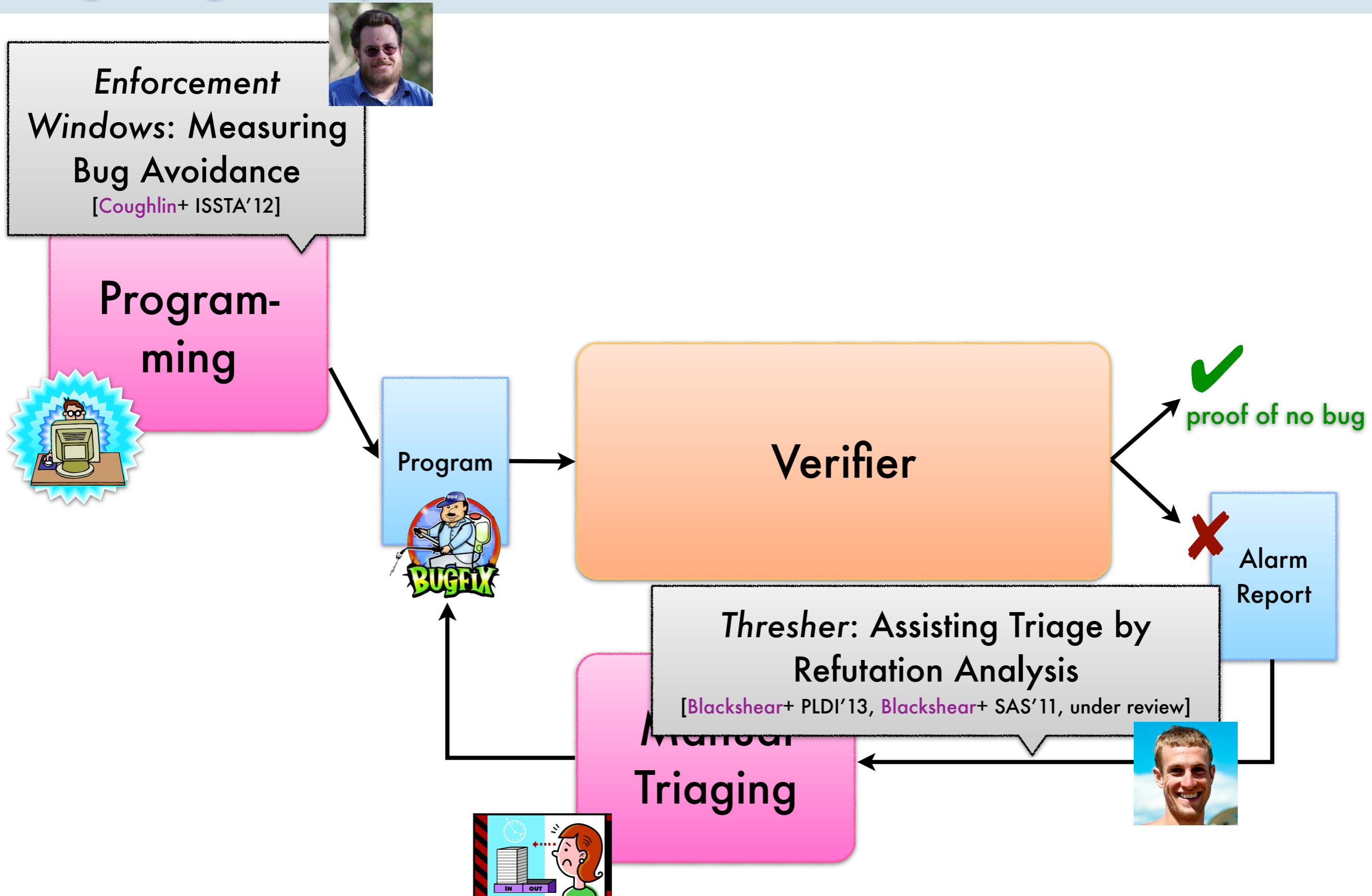




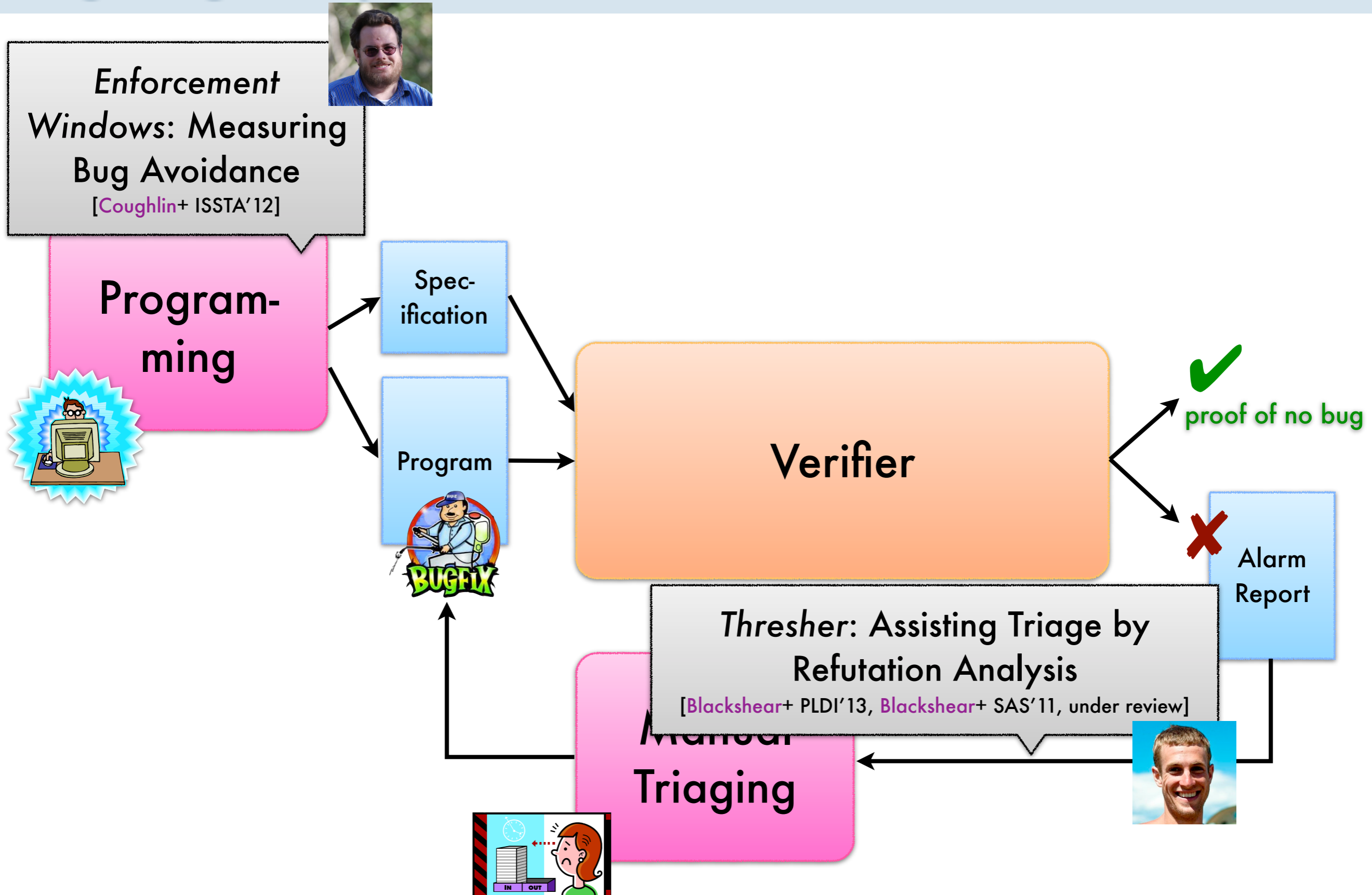
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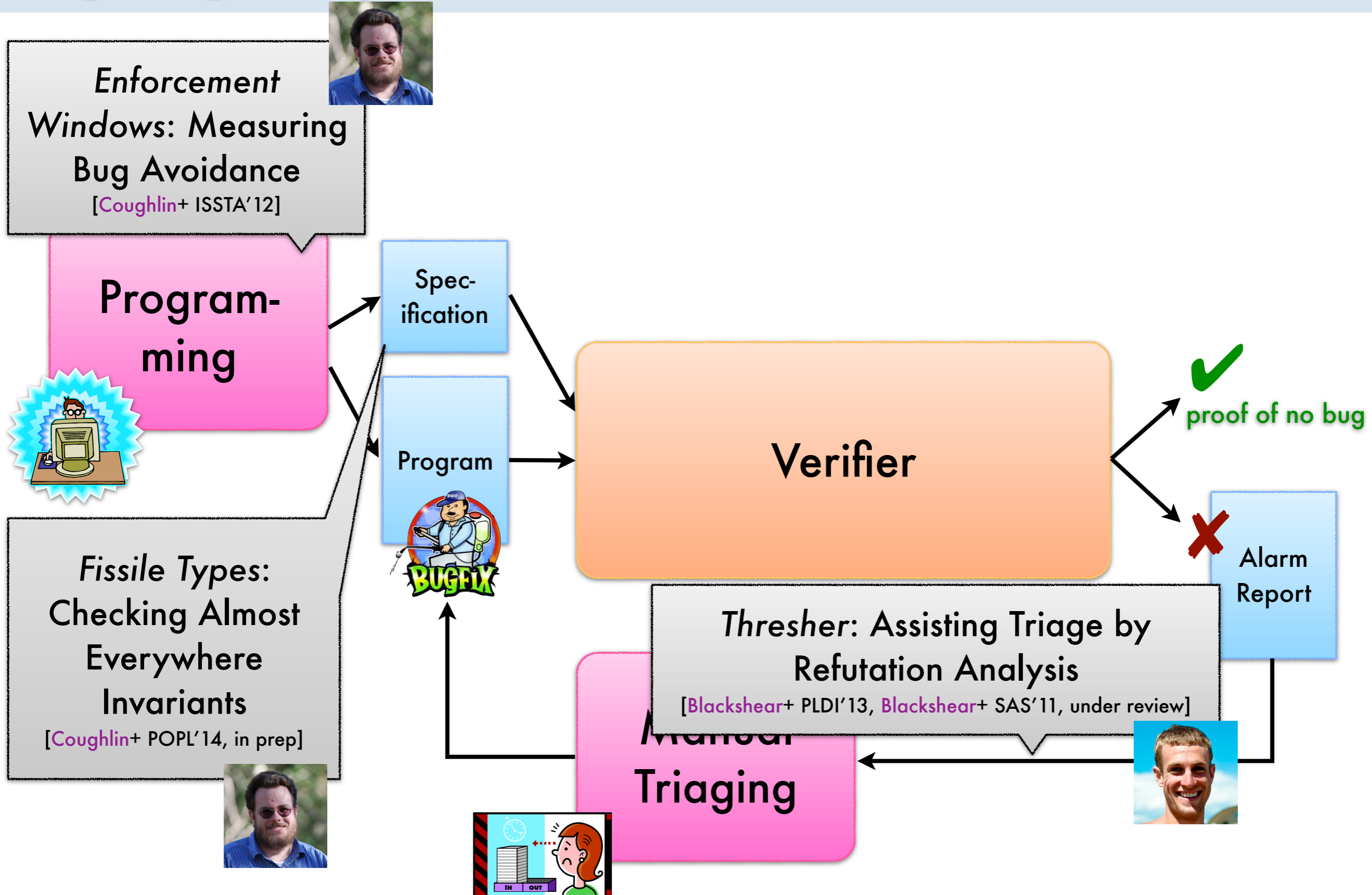
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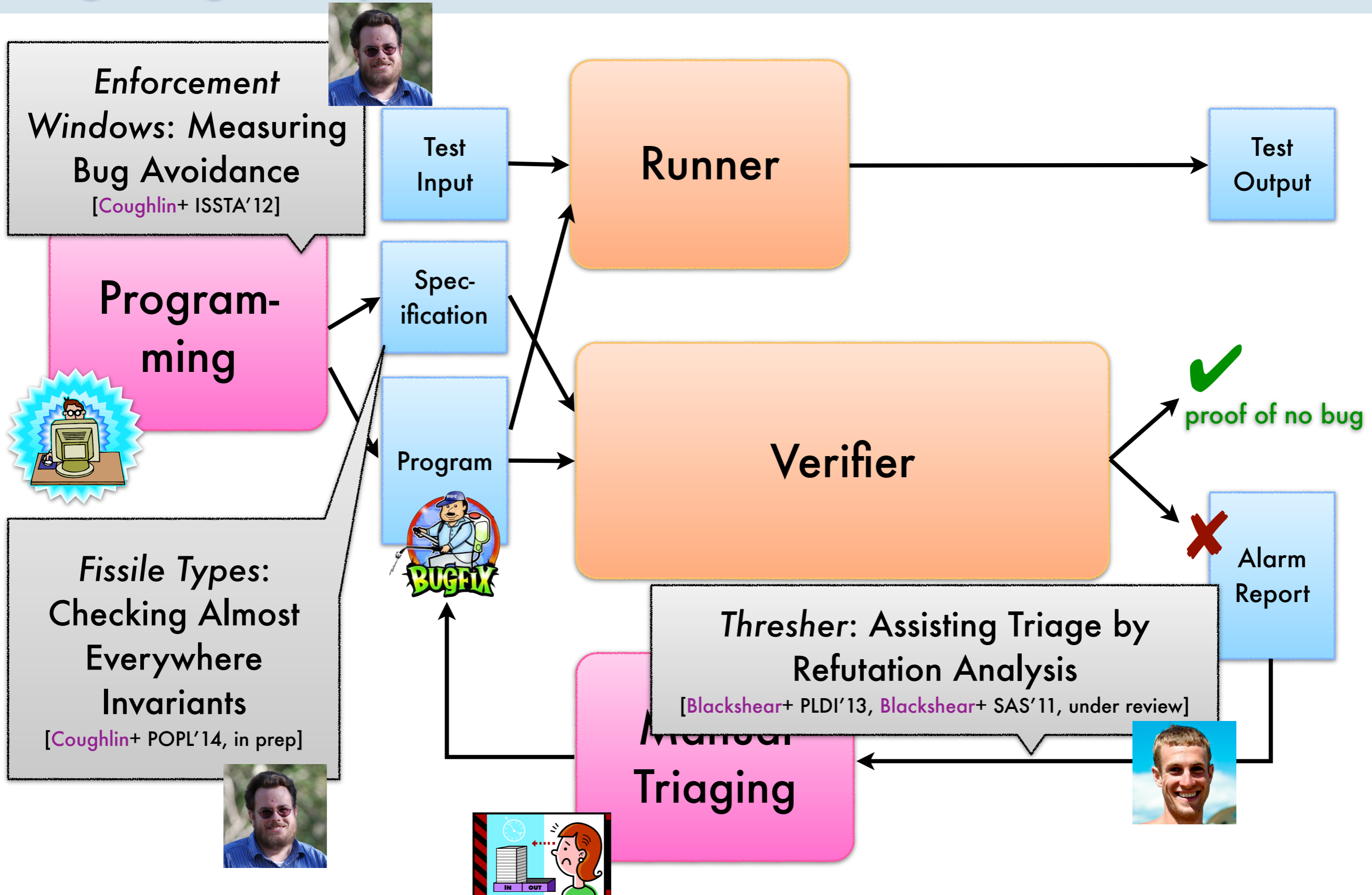
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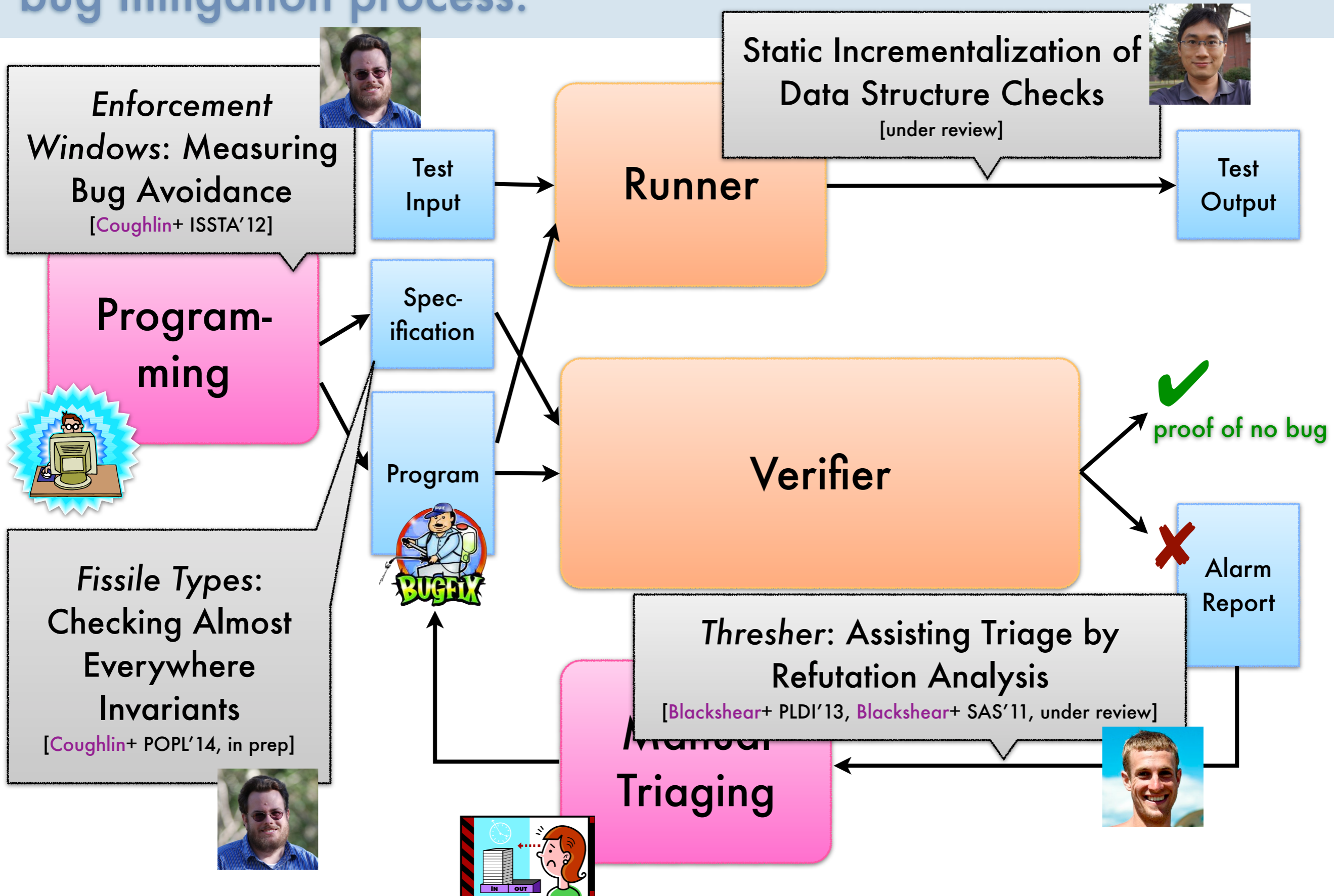
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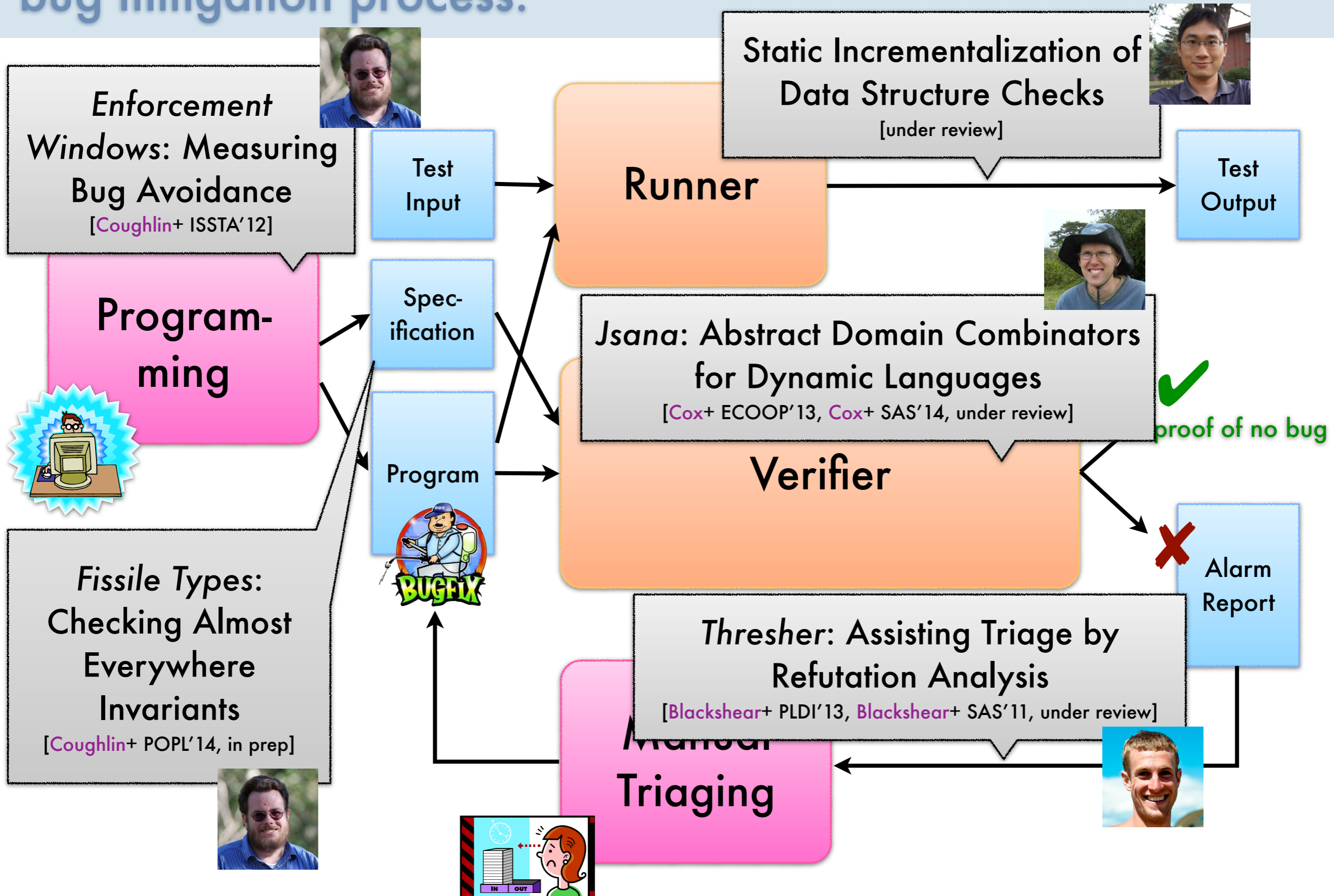
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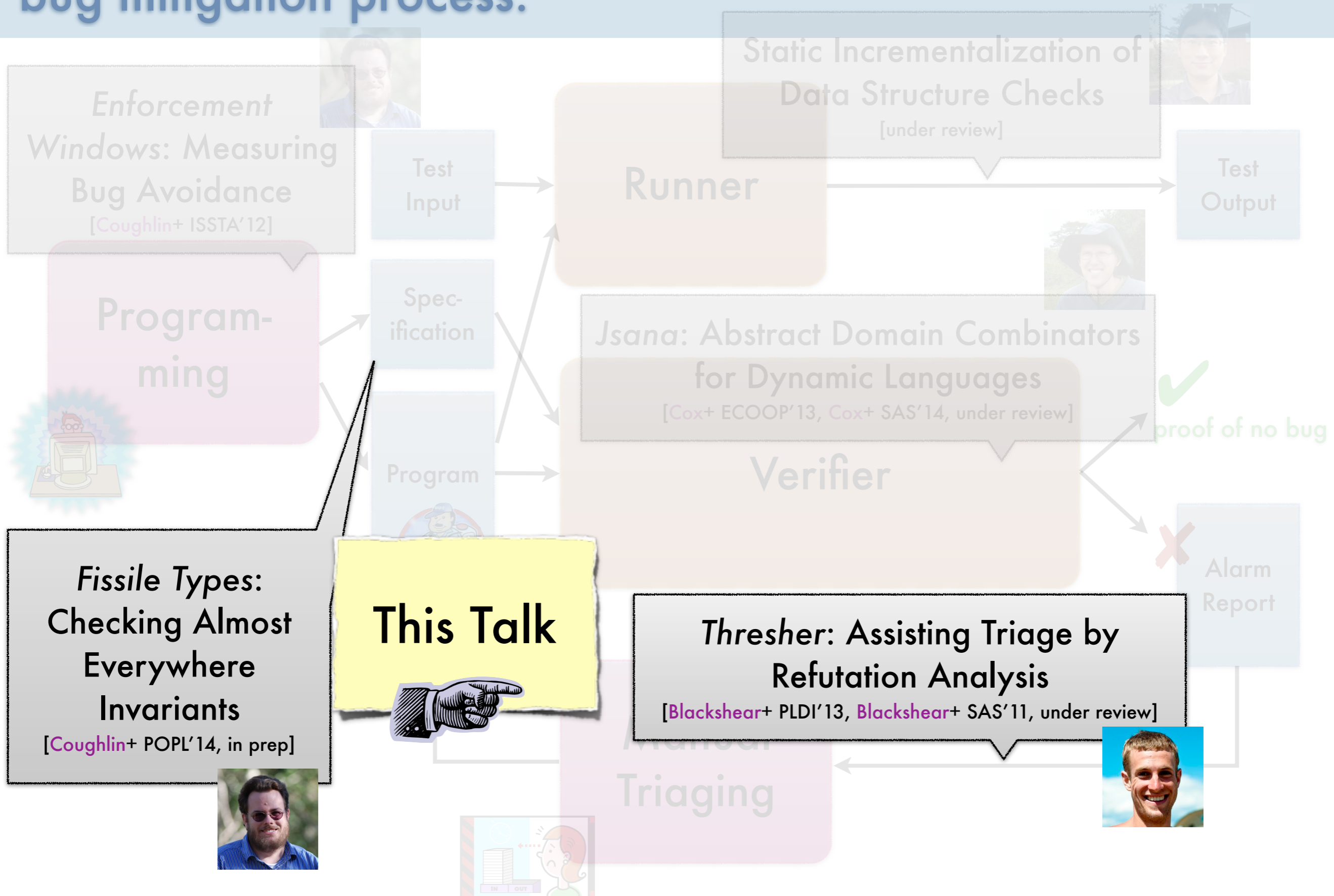
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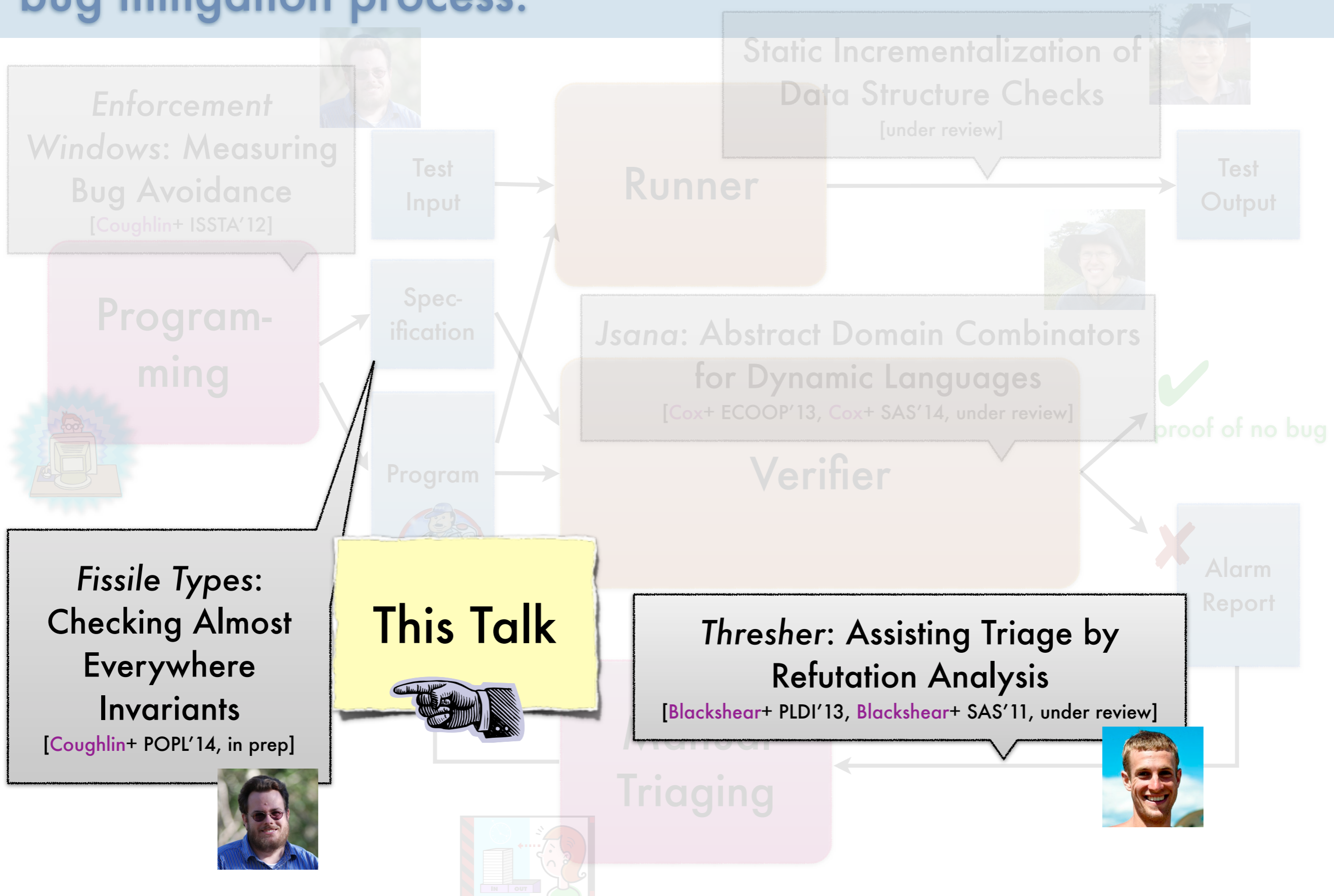


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# This Talk: Highlights

## 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
- ▶ 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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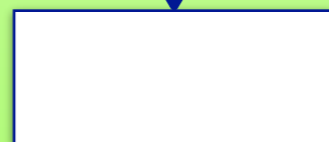
**Can an object ever be reached from another object via pointer dereferences?**

# What are heap reachability queries?

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

Is there a program execution where at some time variable

x



of type T ?

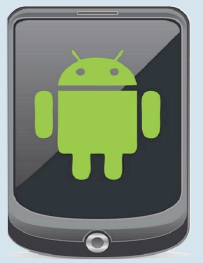
Example



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



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



stackoverflow

Questions

Tags

Tour


Users

## Android: Crash on rotation, horizontal to vertical

Crash is detected after rotating phone in Gmail Sync now view 

[phonegap](#) >

[important bug]cordova 1.9 crash on rotation android

5 posts by 2 authors  



stackoverflow

Questions

Tags

Tour

Users

## App crashes when rotating Samsung phone



# androidterm

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for

★ **Issue 20: Crashes when rotating phone horizontally**

1 person starred this issue and may be notified of changes.

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



stackoverflow

Questions

Tags

Tour

Users

Android: Crash on rotation, horizontal to

How can you have memory leaks with a garbage collected run-time?

phonegap >

## AndroidTerm

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for

★ **Issue 20: Crashes when rotating phone horizontally**

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Activity objects  
encapsulate the UI



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of type Activity



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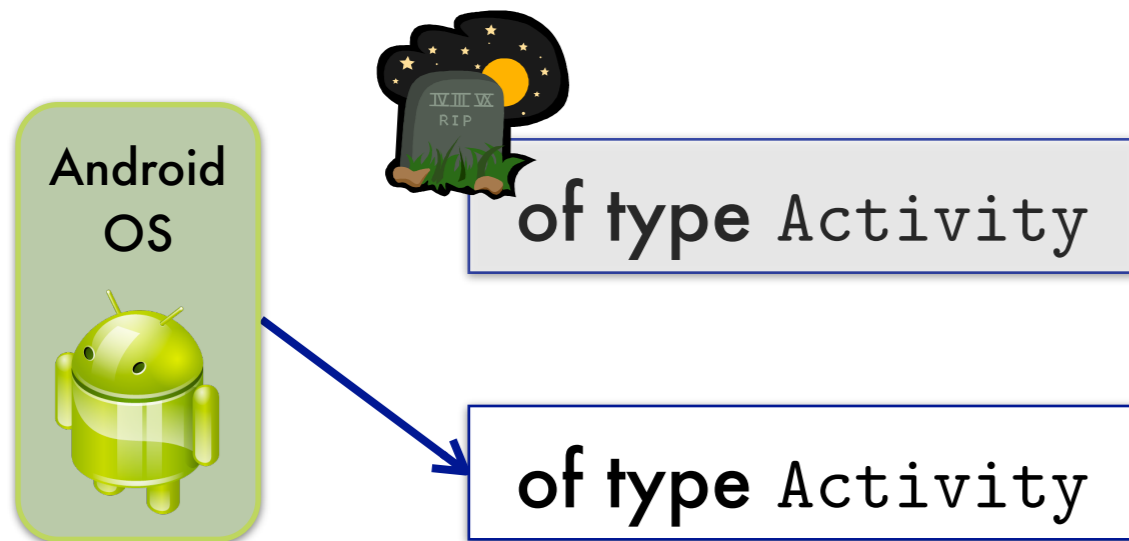


of type Activity

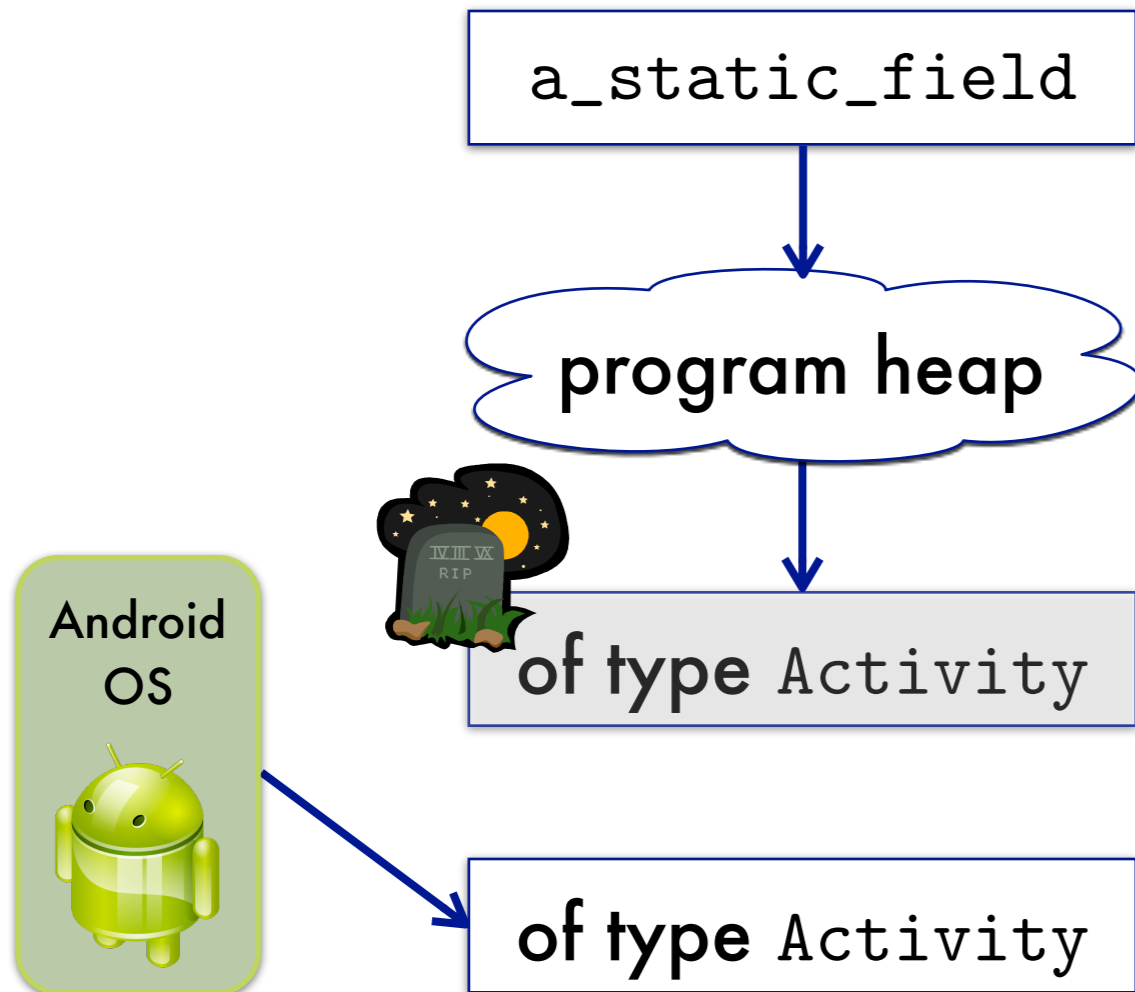


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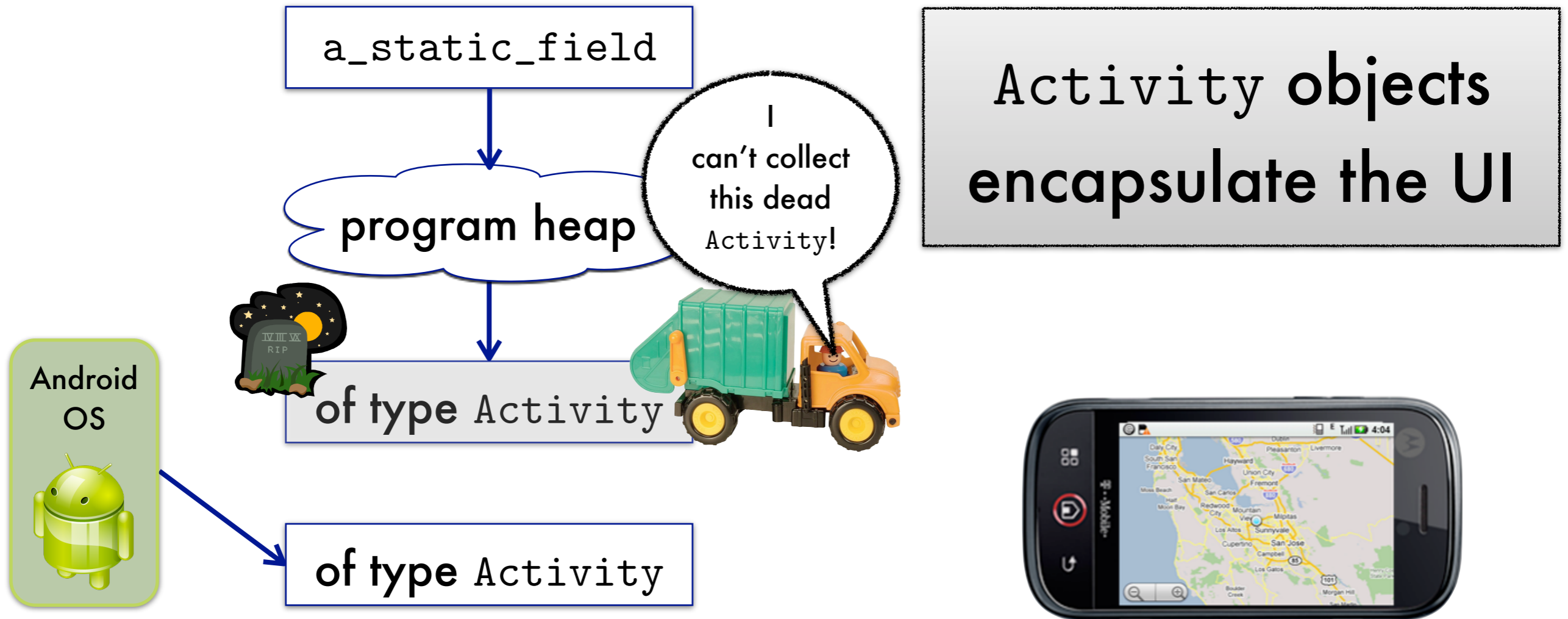


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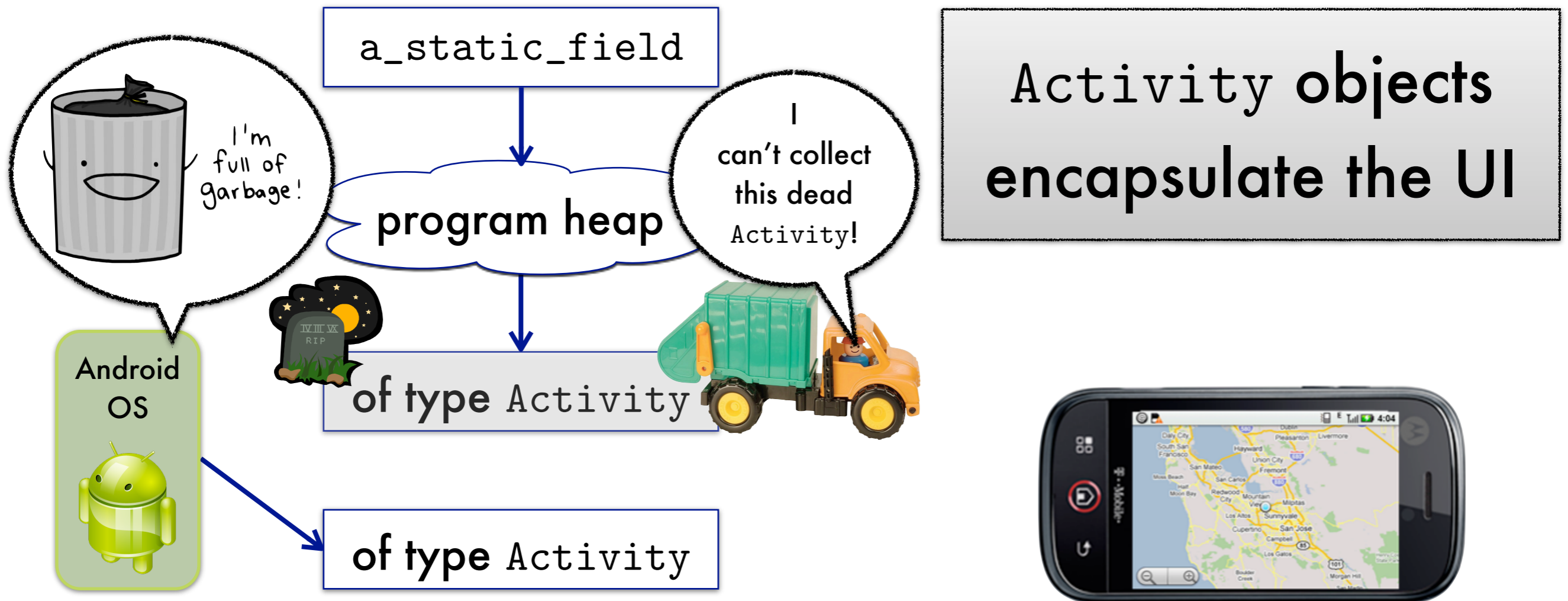




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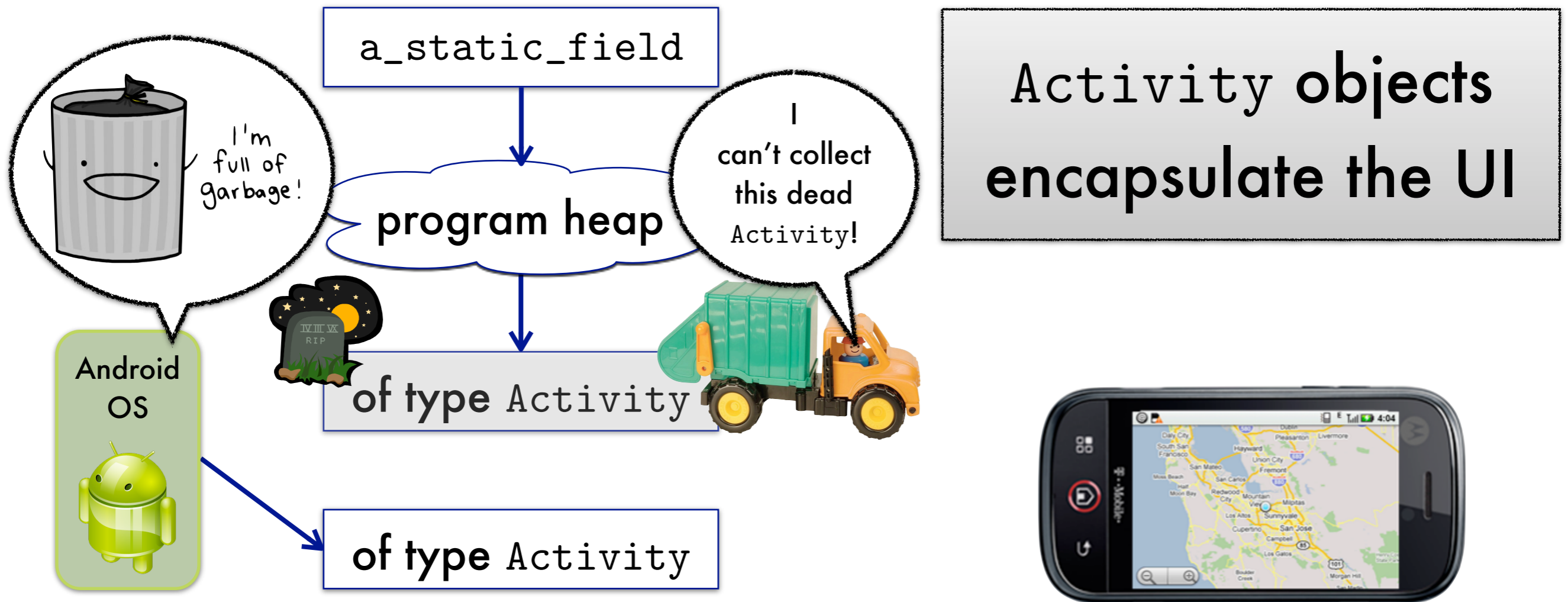
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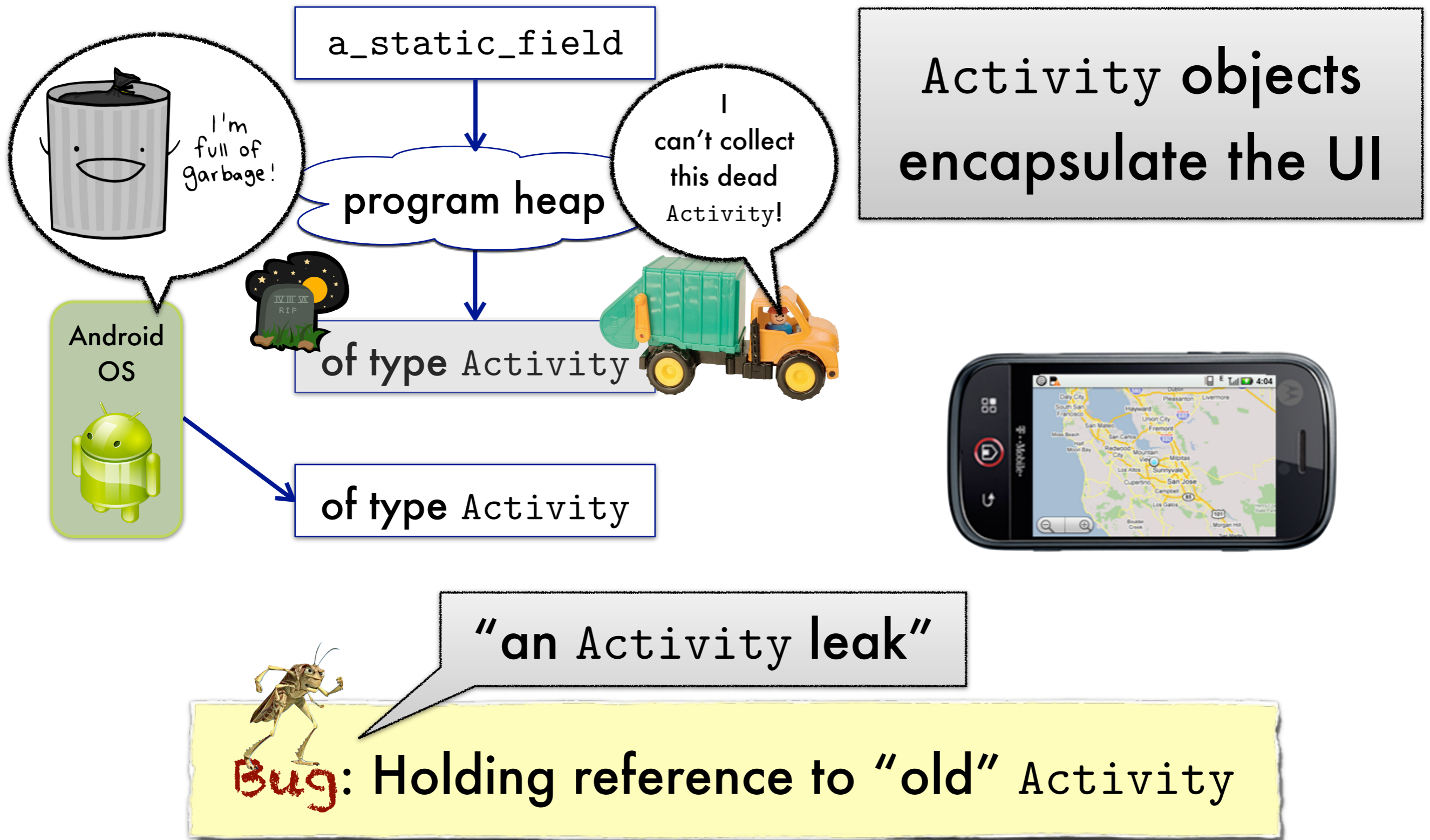


# Android memory leaks underly rotation-based crashes.



 **Bug:** Holding reference to "old" Activity

# Android memory leaks underly rotation-based crashes.



# The expert recommendation ...



# The expert recommendation ...

A screenshot of a web browser displaying an article from the Android Developers Blog. The browser's address bar shows the URL: android-developers.blogspot.dk/2009/01/avoiding-memory-leaks.html. The page features a dark blue header with the Android Developers Blog logo and a grid of icons. Below the header, the article is dated 19 JANUARY 2009 and titled "Avoiding memory leaks". The text explains that Android applications are limited to 16 MB of heap memory and discusses the importance of avoiding memory leaks by not holding long-lived references to Context. A code snippet is provided, showing an @Override method onCreate that initializes a TextView with the text "Leaks are bad". The left sidebar contains a search bar and an archive menu listing posts by year and month.

Questions containing 'andro' x Issues - android - Android - x Android Developers Blog: Av x Android Developers Blog: Me x

android-developers.blogspot.dk/2009/01/avoiding-memory-leaks.html

Android Developers Blog

Developers

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
protected void onCreate(Bundle state) {
    super.onCreate(state);

    TextView label = new TextView(this);
    label.setText("Leaks are bad");
}
```

SEARCH

ARCHIVE

- ▶ 2012 (31)
- ▶ 2011 (68)
- ▶ 2010 (73)
- ▼ 2009 (63)
  - ▶ December (7)
  - ▶ November (5)
  - ▶ October (5)
  - ▶ September (8)
  - ▶ August (2)
  - ▶ July (1)

# The expert recommendation ...



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

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Developers

19 JANUARY 2009

## Avoiding memory leaks

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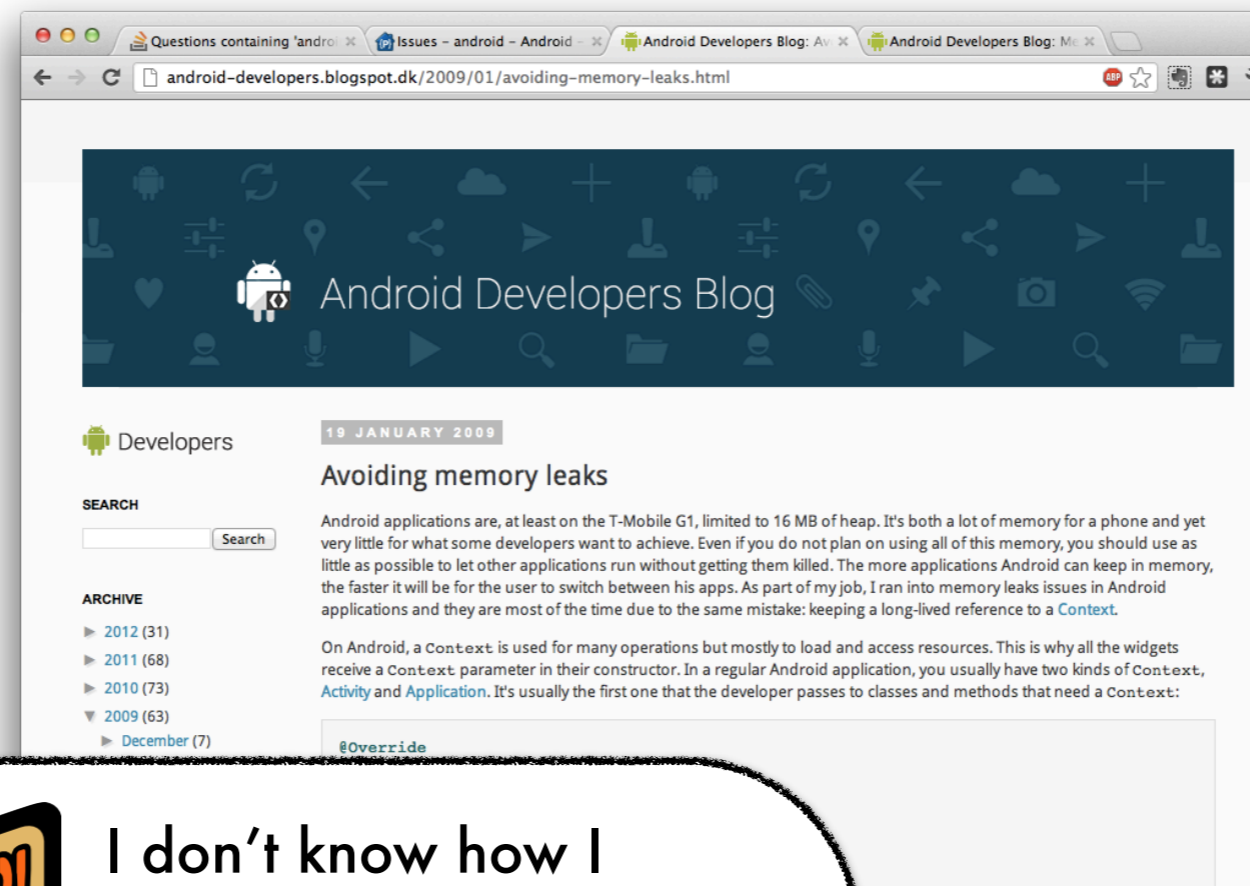
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# The expert recommendation ...



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



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



# 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 ...



The screenshot shows a web browser window displaying a blog post. The browser's address bar shows the URL: `android-developers.blogspot.dk/2011/03/memory-analysis-for-android.html`. The page header features the Android Developers Blog logo and a navigation bar with various icons. The main content area includes a search bar, an archive list for the years 2012 and 2011, and the article title "Memory Analysis for Android Applications" dated 24 MARCH 2011. The article text discusses memory management in the Dalvik runtime and mentions tools like the Allocation Tracker and heap dumps. A small portrait of the author, Patrick Dubroy, is visible on the right side of the article.

Developers

24 MARCH 2011

## Memory Analysis for Android Applications

*[This post is by Patrick Dubroy, an Android engineer who writes about programming, usability, and interaction on his [personal blog](#). — Tim Bray]*

The Dalvik runtime may be garbage-collected, but that doesn't mean you can ignore memory management. You should be especially mindful of memory usage on mobile devices, where memory is more constrained. In this article, we're going to take a look at some of the memory profiling tools in the Android SDK that can help you trim your application's memory usage.

Some memory usage problems are obvious. For example, if your app leaks memory every time the user touches the screen, it will probably trigger an `OutOfMemoryError` eventually and crash your app. Other problems are more subtle, and may just degrade the performance of both your app (as garbage collections are more frequent and take longer) and the entire system.

### Tools of the trade

The Android SDK provides two main ways of profiling the memory usage of an app: the *Allocation Tracker* tab in DDMS, and heap dumps. The Allocation Tracker is useful when you want to get a sense of what kinds of allocation are happening over a

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



## 1. Run the app

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



24 MARCH 2011

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Dalvik Debug Monitor

Info Threads VM Heap Allocation Tracker Sysinfo Emulator Control Event Log

Heap updates will happen after every GC for this client

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

Display: Stats

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



# 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

Dalvik Debug Monitor

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Eclipse Memory Analyzer

leak-converted.hprof

list\_objects (selection of 'byte[]' -inbound)

Class Name	Shallow Heap	Retained Heap
<Regex>	<Numeric>	<Numeric>
byte[8] @ 0x429b69c8 HPDS...	24	24
byte[2797568] @ 0x426fe780 '2' & !'2\$ (3%&##+ . (...\$...%...\$...#...+...7&2>*0	2,797,584	2,797,584
mBuffer android.graphics.Bitmap @ 0x40a50fa8	40	2,797,640
value java.util.HashMap\$HashMapEntry @ 0x40a4ceb8	24	5,595,472
[13] java.util.HashMap\$HashMapEntry[16] @ 0x40805440	80	32,802,960
table java.util.HashMap @ 0x40801a98	48	32,803,008
sBitmapCache class com.example.android.hcgallery.ContentFragment (	8	32,803,056
<class> com.example.android.hcgallery.ContentFragment @ 0x4080	128	384
value java.util.HashMap\$HashMapEntry @ 0x408009c0	24	152
Σ Total: 2 entries		
byte[2797568] @ 0x42453768 %..jS .+& .61+.HA.;F79.92.4-'.C.8.MEB.@.8.'...-?;<	2,797,584	2,797,584
byte[2797568] @ 0x421a8750 .....z.FRF.Pi.P.OXU.NWT.ZUY.ZUY.yvo.....lt\..u.e.z.\.syU.	2,797,584	2,797,584
byte[2797568] @ 0x41efd120 njg.pli.kgd.b^[\da\olq.tql.qni.roh.urk.wtm.spl.lib.he^k	2,797,584	2,797,584
byte[3252224] @ 0x41be3108 .....#.....	3,252,240	3,252,240
byte[2797568] @ 0x419380f0 .....#.....	2,797,584	2,797,584
byte[2797568] @ 0x4168d0d8 d.B.d.B.d.@.d.@.f.7.g.@.h.B.h.B.i.B.h.B.i.C.g.C.f.B.f.C	2,797,584	2,797,584
byte[2797568] @ 0x413e20c0 cR@.eT@.eVA.dU@.aR@.' Q<.' Q>@.bS@.bS@.bS@.e'	2,797,584	2,797,584
byte[2797568] @ 0x411370a8 .....#.....	2,797,584	2,797,584
byte[2797568] @ 0x40e8c090 .....#.....	2,797,584	2,797,584
byte[1572864] @ 0x40d0c078 .....#.....	1,572,880	1,572,880
byte[2797568] @ 0x40a61060 .....#.....	2,797,584	2,797,584
byte[62100] @ 0x40a51db8 .....#.....	62,112	62,112
byte[24] @ 0x40a4cd11 .....#.....	40	40
byte[4096] @ 0x40a4aa50 .....#.....	4,112	4,112
byte[24] @ 0x40a4a7a1 .....#.....	40	40
byte[4096] @ 0x40a48148 .....#.....	4,112	4,112
byte[24] @ 0x40a464f1 .....#.....	40	40
byte[84] @ 0x40a40560 .....#.....	96	96
byte[768] @ 0x40a40200 .....#.....	784	784
byte[1572864] @ 0x408beab8 2@3.2@3.4@4.SA5.6A3.471.3>0.6A1.8C3.8E4.8E'	1,572,880	1,572,880
byte[84] @ 0x408ba188 .....#.....	96	96
byte[960] @ 0x408b9d68 .....#.....	976	976
byte[84] @ 0x408b9a48 .....#.....	96	96
byte[960] @ 0x408b9628 .....#.....	976	976
byte[56] @ 0x408b9318 .....#.....	72	72
byte[192] @ 0x408b91f8 .....#.....	208	208

36M of 81M

# 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?

Dalvik Debug Monitor

Info Threads VM Heap Allocation Tracker Sysinfo Emulator Control Event Log

Heap updates will happen after every GC for this client

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

Display: Stats

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

Eclipse Memory Analyzer

Inspector

leak-converted.hprof

list\_objects [selection of 'byte[]' -inbound]

Class Name	Shallow Heap	Retained Heap
<Regex>	<Numeric>	<Numeric>
byte[8] @ 0x429b69c8 HPDS...	24	24
byte[2797568] @ 0x426fe780 '2'&!1'2\$(3%&##+ (.!\$...%...\$...#...+...7&2>*0	2,797,584	2,797,584
mBuffer android.graphics.Bitmap @ 0x40a50fa8	40	2,797,640
value java.util.HashMap\$HashMapEntry @ 0x40a4ceb8	24	5,595,472
[13] java.util.HashMap\$HashMapEntry[16] @ 0x40805440	80	32,802,960
table java.util.HashMap @ 0x40801a98	48	32,803,008
sBitmapCache class com.example.android.hcgallery.ContentFragment (	8	32,803,056
<class> com.example.android.hcgallery.ContentFragment @ 0x4080...	128	384
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Σ Total: 2 entries		
byte[2797568] @ 0x42453768 %..j5 .+& .61+.HA.;F79.92.4-'.C.8.MEB.@.8.'...-)?;<	2,797,584	2,797,584
byte[2797568] @ 0x421a8750 .....z.FRF.P!P.OXU.NWT.ZUY.ZUY.yvo.....lt .u.e.z .syU.	2,797,584	2,797,584
byte[2797568] @ 0x41efd120 njg.pli.kgd.b^[da .olg.tql.qni.roh.urk.wtm.spi.lib.he^k	2,797,584	2,797,584
byte[3252224] @ 0x41be3108 .....	3,252,240	3,252,240
byte[2797568] @ 0x419380f0 .....	2,797,584	2,797,584
byte[2797568] @ 0x4168d0d8 d.B.d.B.d.@.d.@.f.7.g.@.h.B.h.B.i.B.h.B.i.C.g.C.f.B.f.C	2,797,584	2,797,584
byte[2797568] @ 0x413e20c0 <r>.eT@.eVA.dU@.aR=. 'Q<.'Q>.bS@.bS@.bS@.e'	2,797,584	2,797,584
byte[2797568] @ 0x411370a8 .....	2,797,584	2,797,584

The culprit

## 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

`a_static_field`



`of type Activity` ?

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

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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

with **approximation**

*Hidden Truth*

# 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

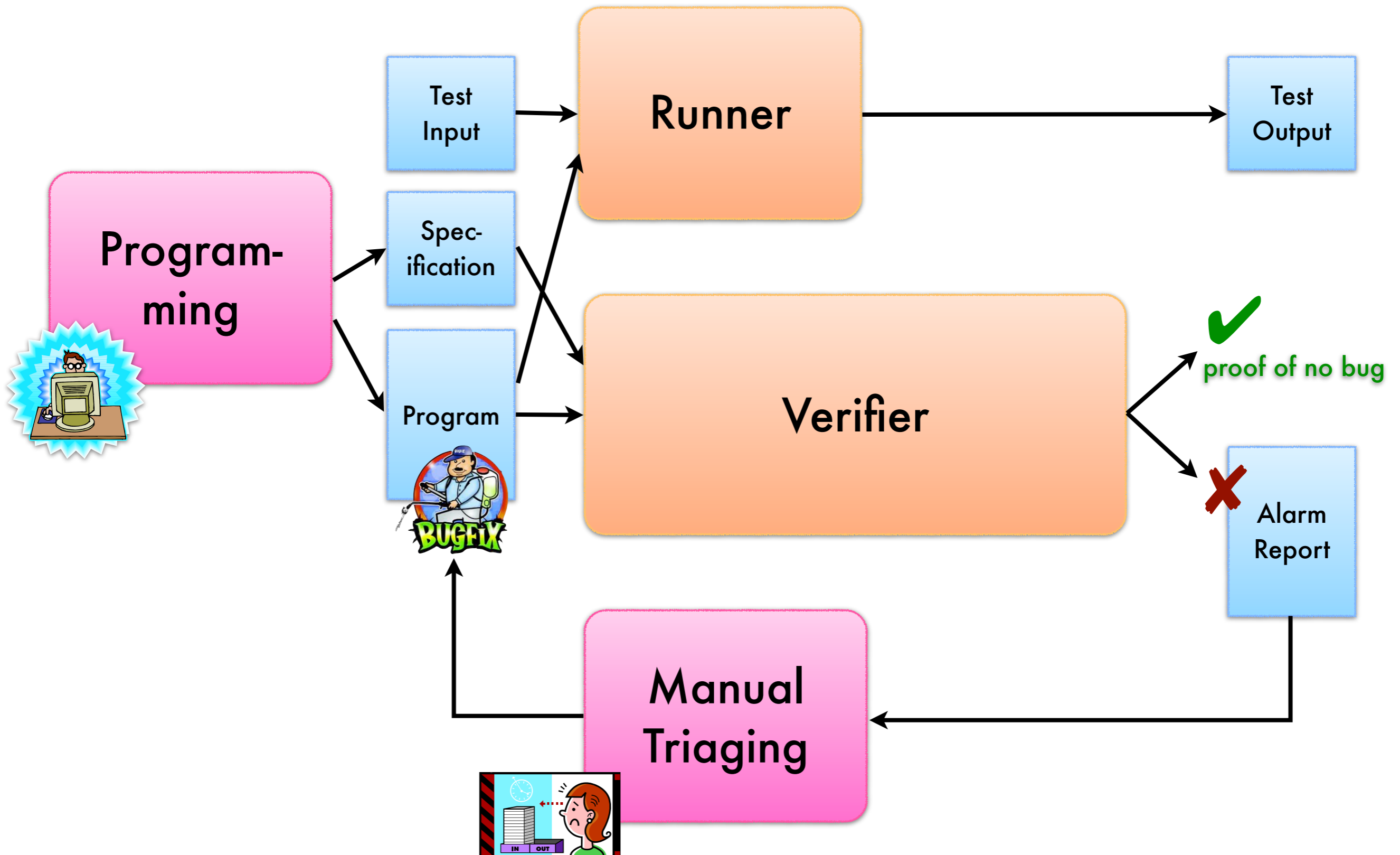
Can be answered with a points-to analysis

with **approximation**

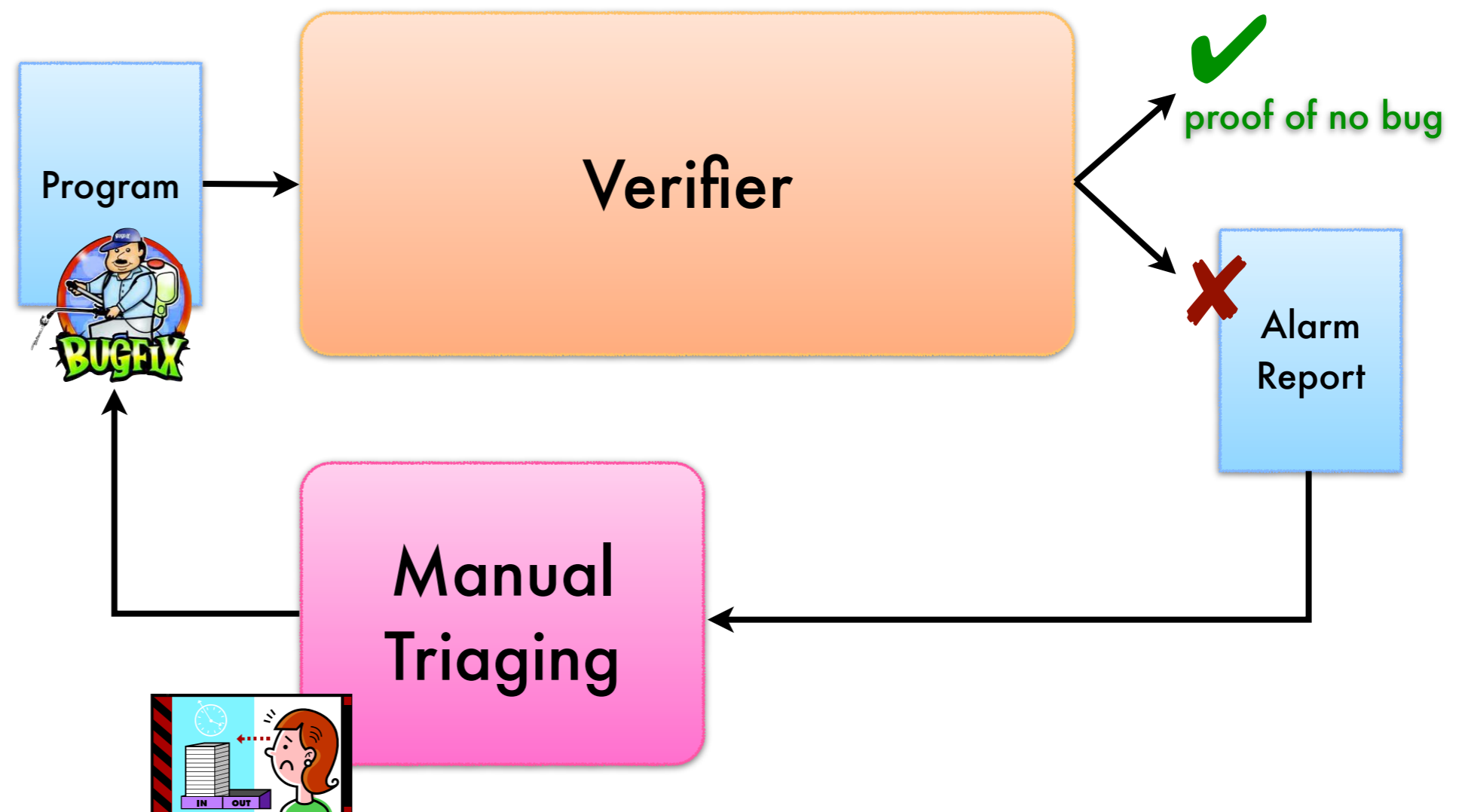
*Hidden Truth*

Some pointer relations **may** be false

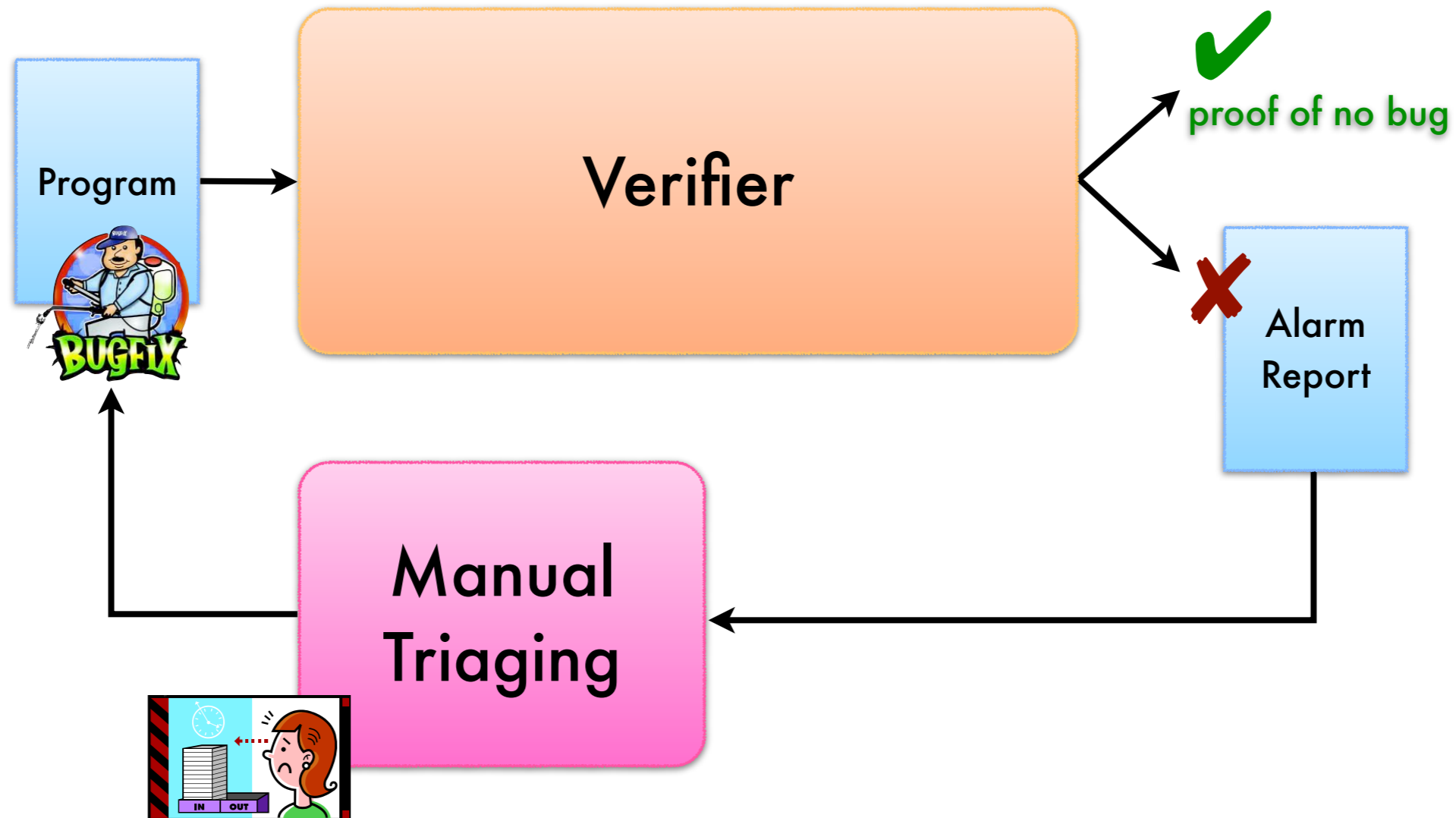
# But with the cooperative approach ...



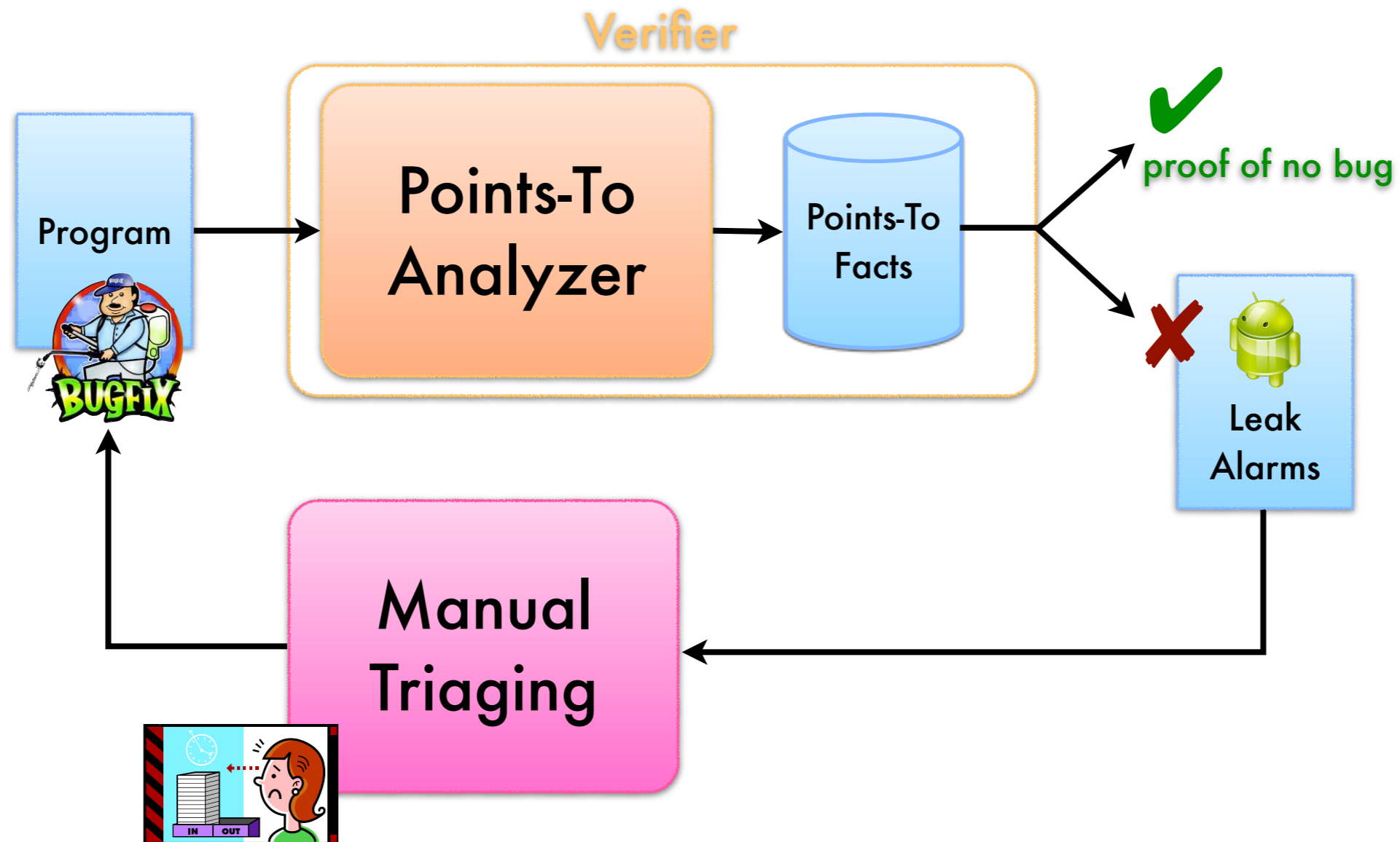
# But with the cooperative approach ...



# Thresher addresses alarm triage in a particularly challenging domain.

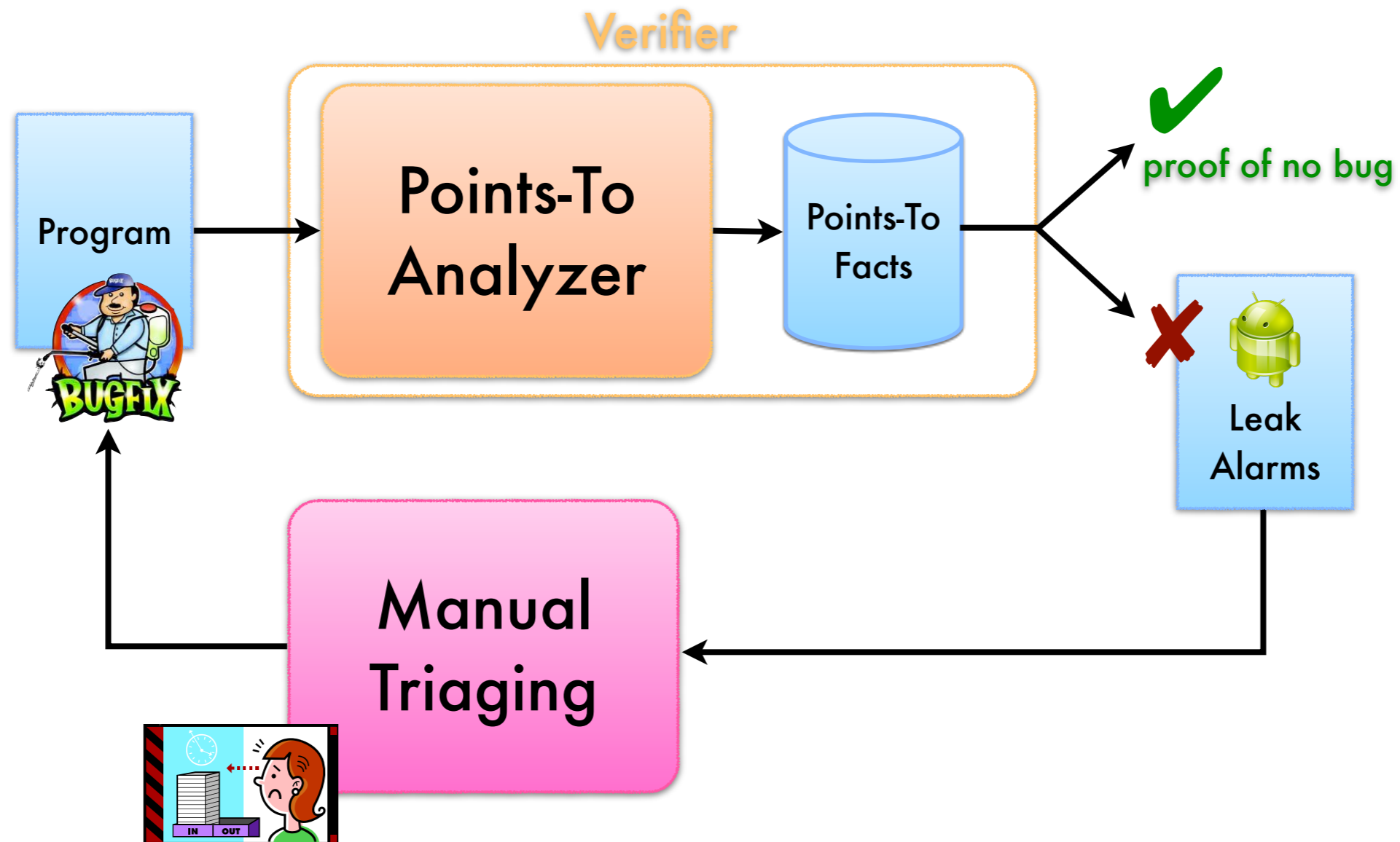


# Thresher addresses alarm triage in a particularly challenging domain.



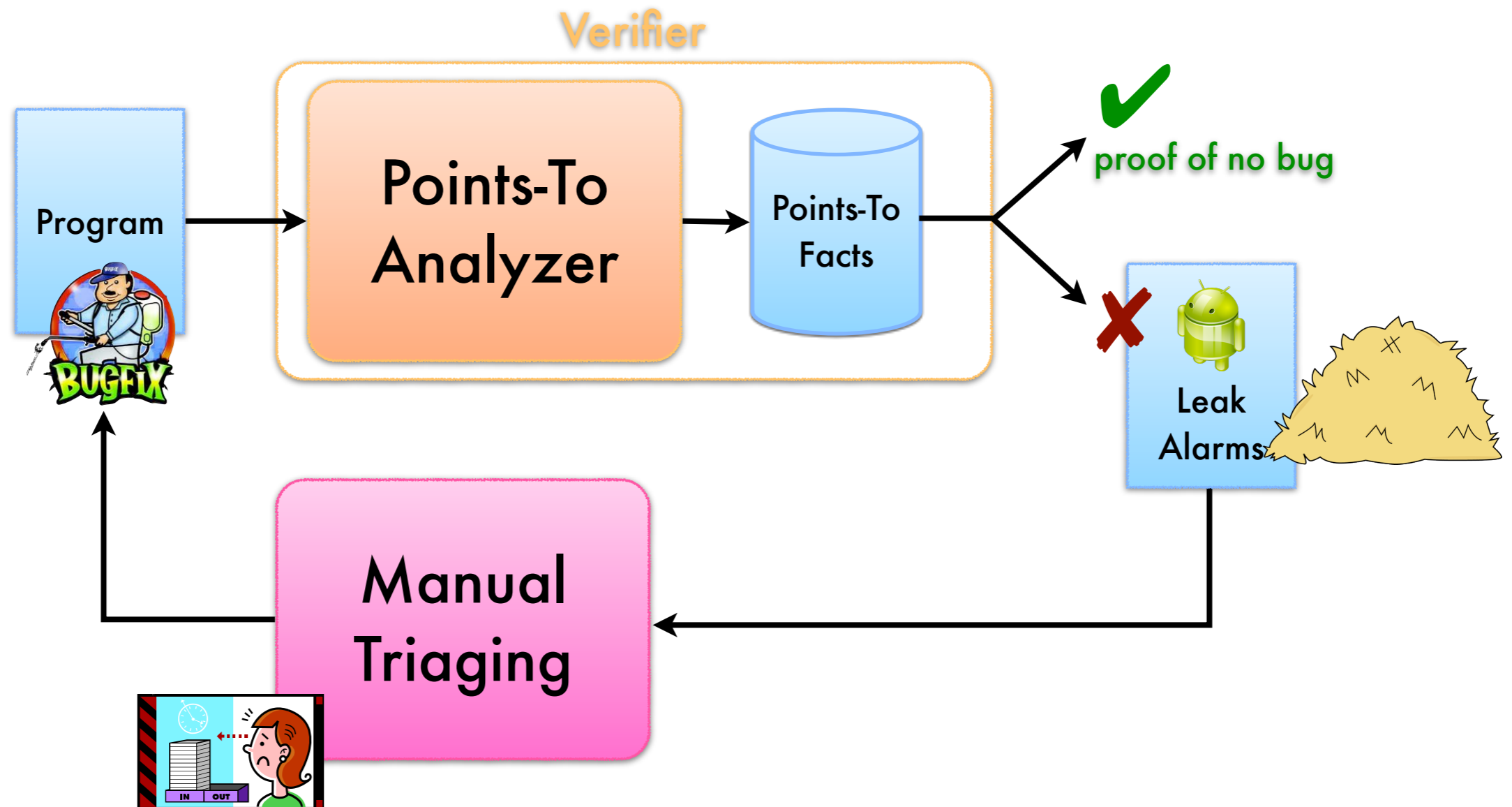


# Thresher addresses alarm triage in a particularly challenging domain.



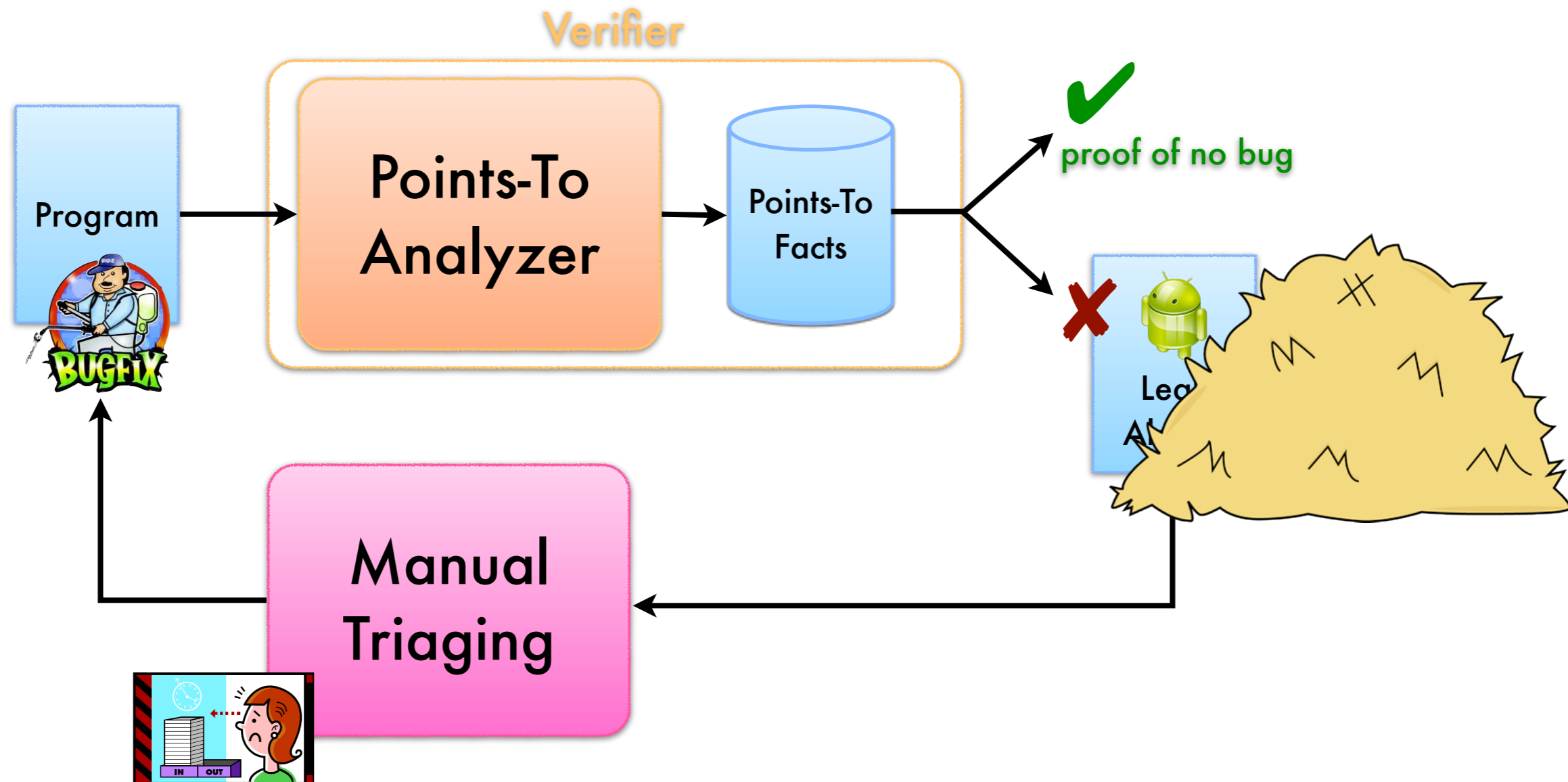
**Known: Precise points-to analysis challenging**

# Thresher addresses alarm triage in a particularly challenging domain.



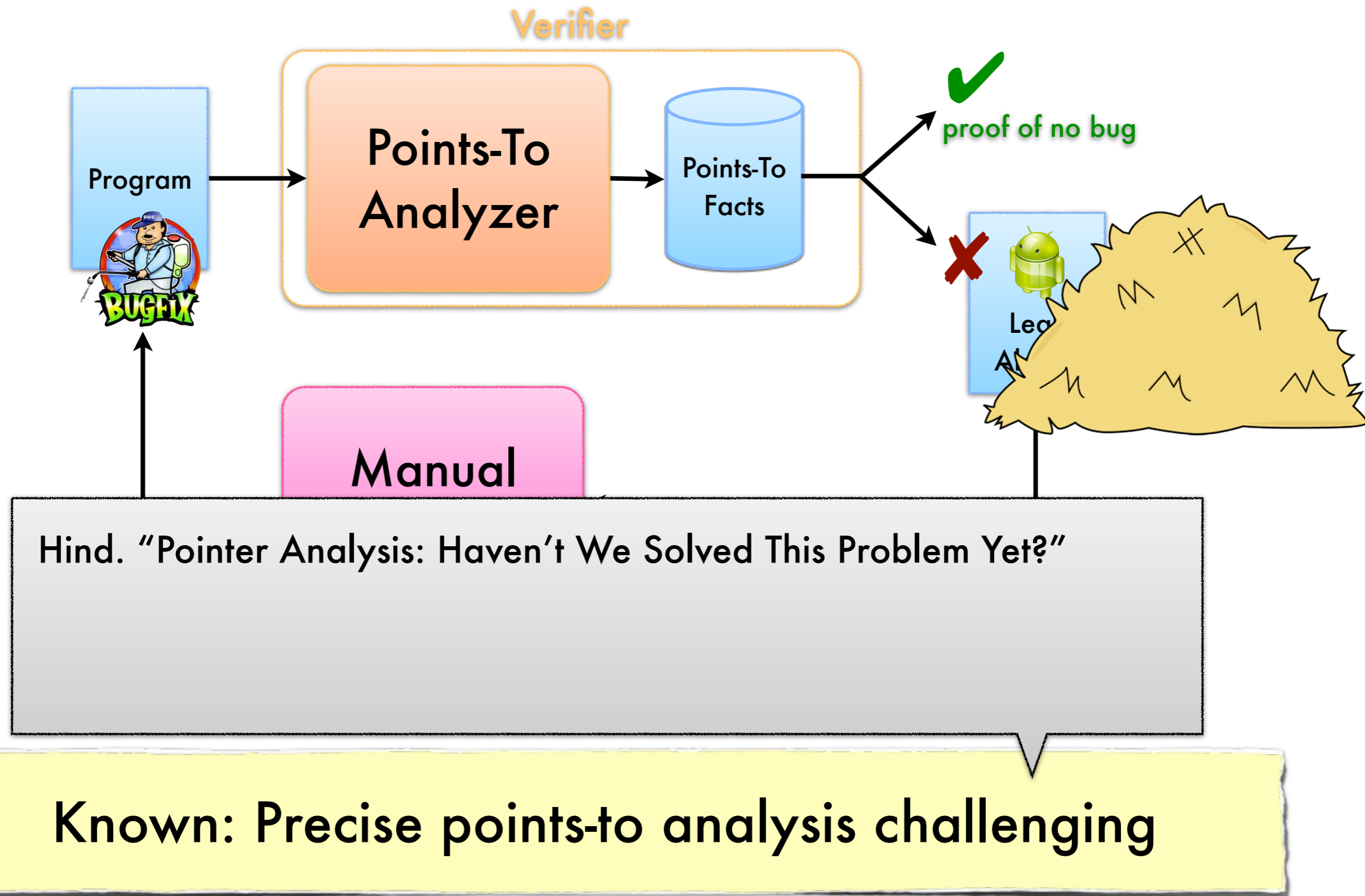
**Known: Precise points-to analysis challenging**

# Thresher addresses alarm triage in a particularly challenging domain.

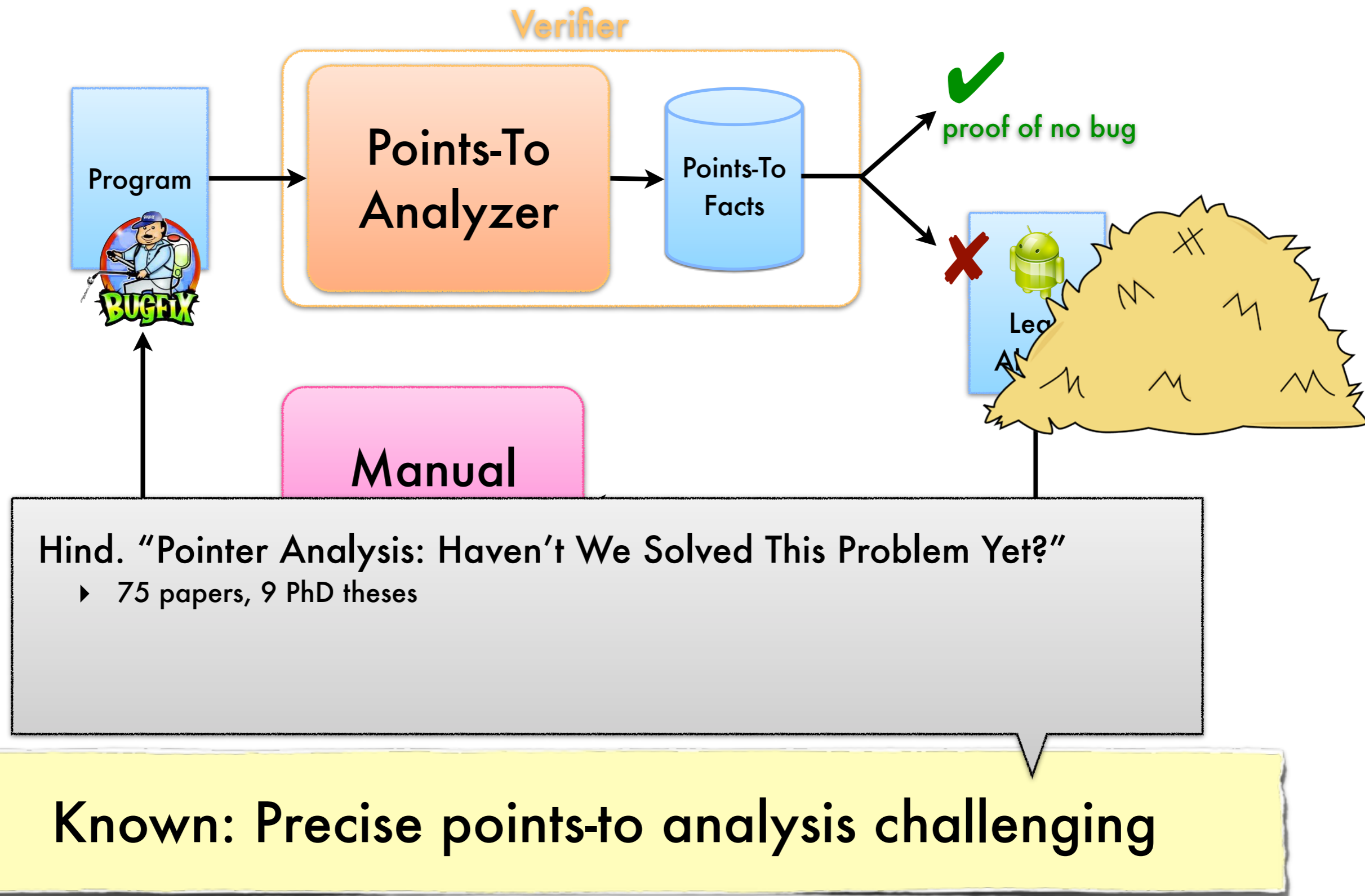


Known: Precise points-to analysis challenging

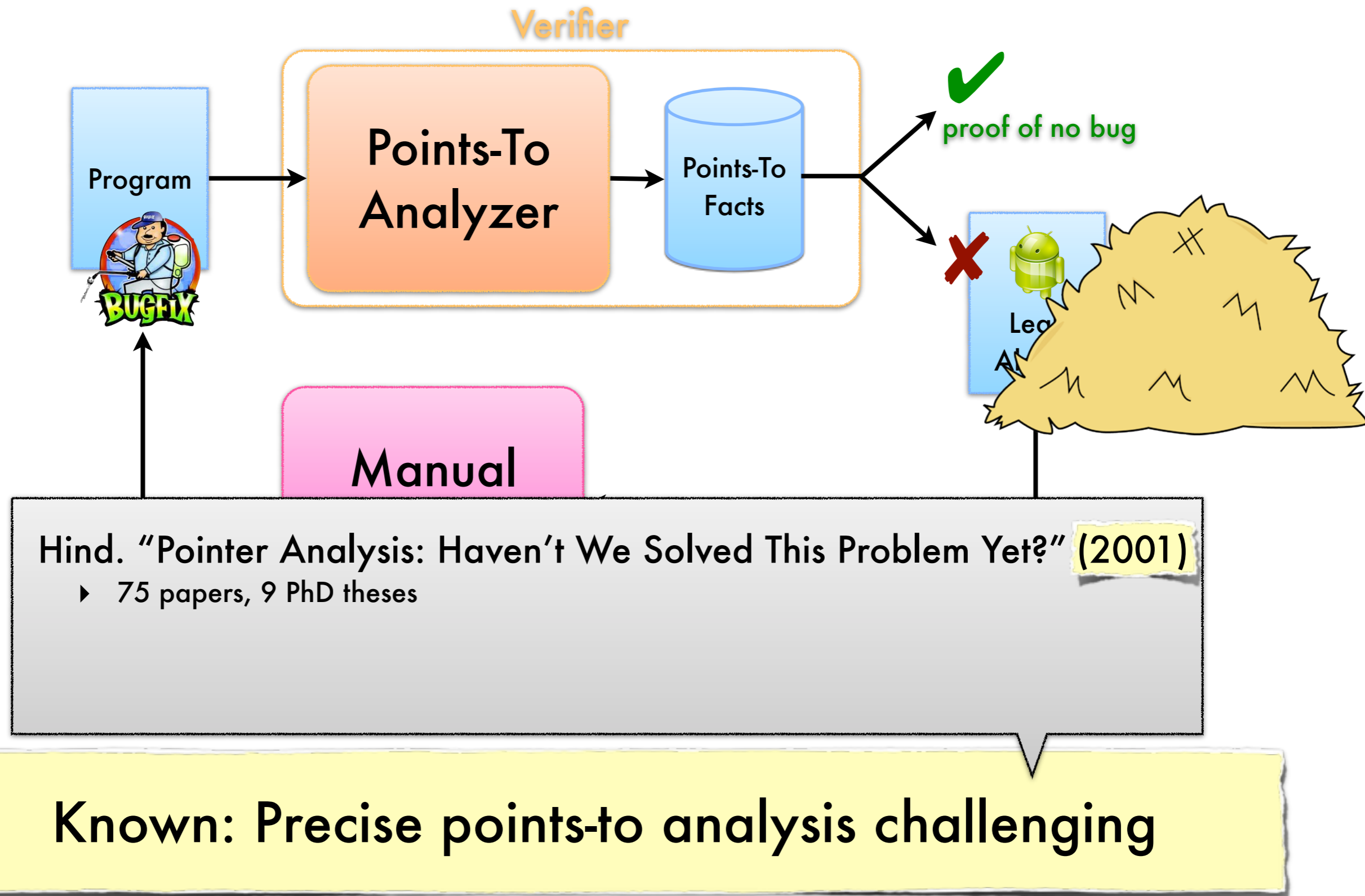
# Thresher addresses alarm triage in a particularly challenging domain.



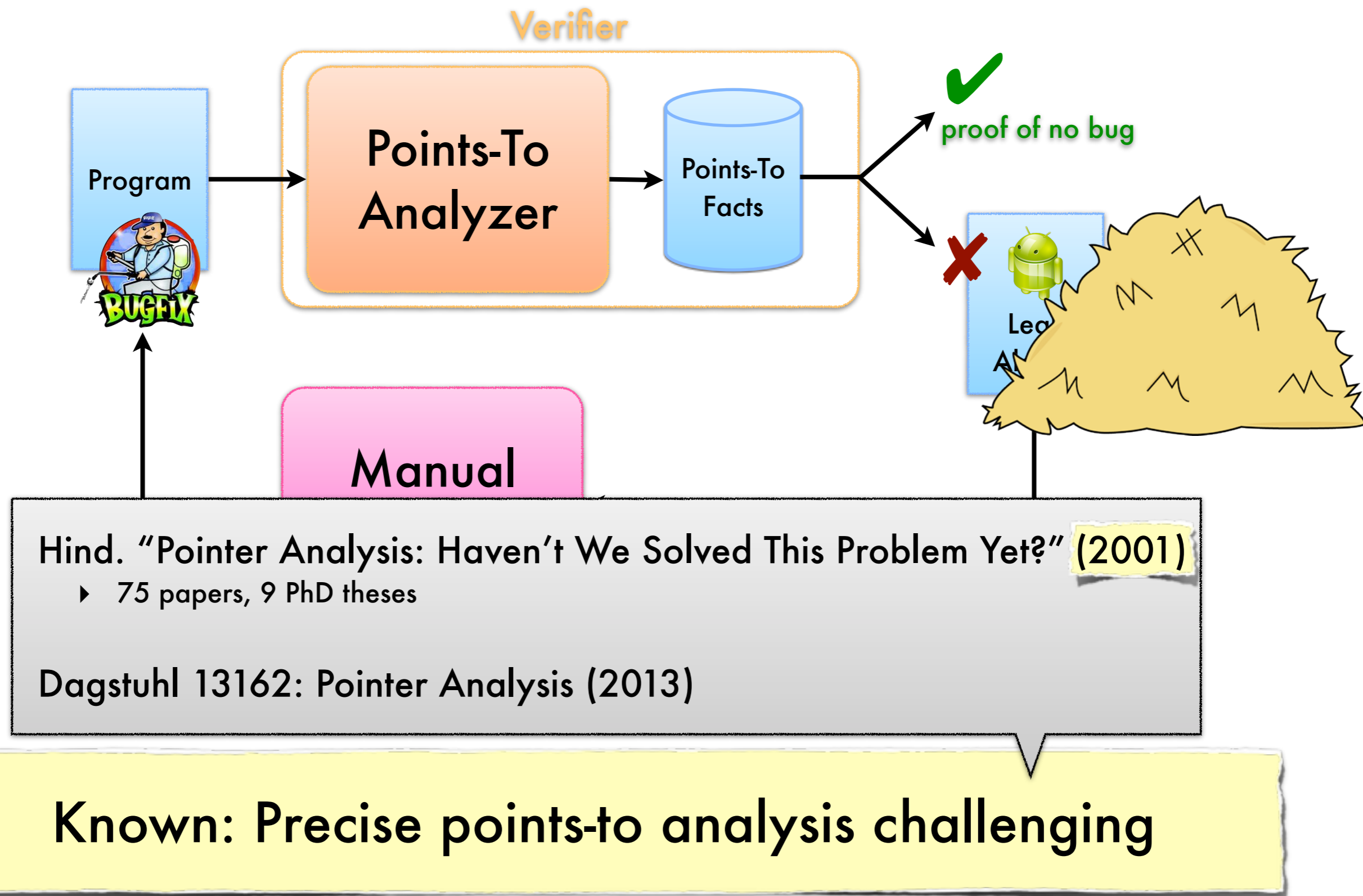
# Thresher addresses alarm triage in a particularly challenging domain.



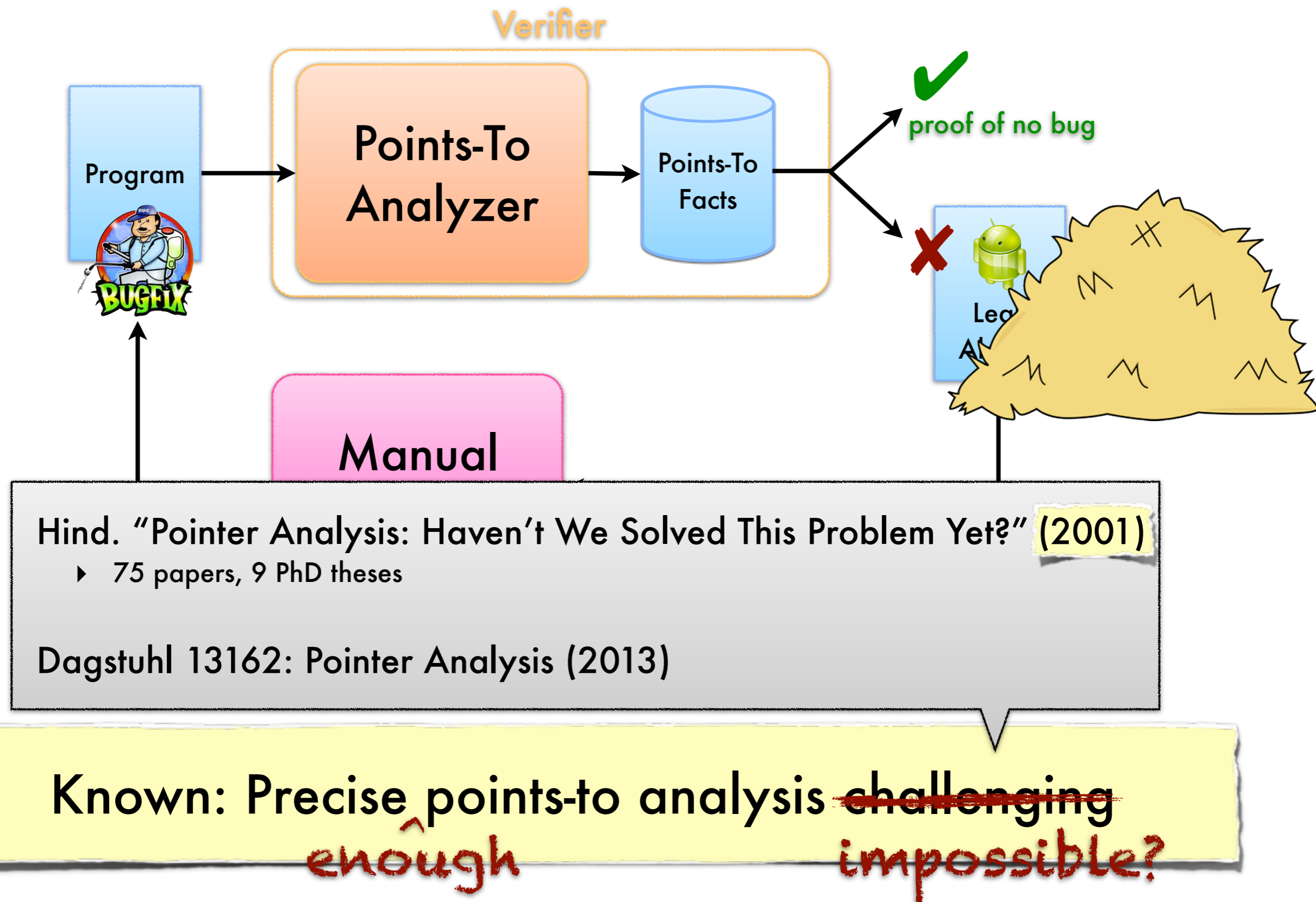
# Thresher addresses alarm triage in a particularly challenging domain.



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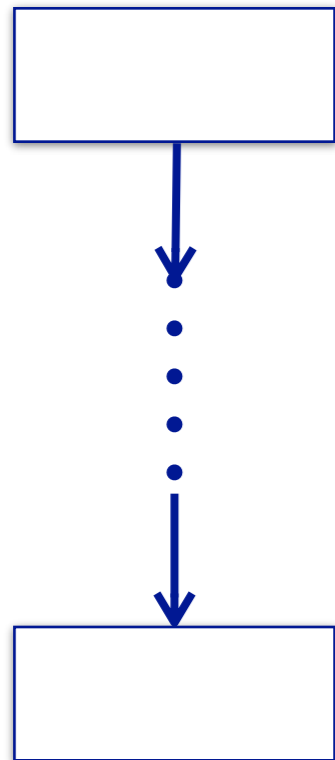
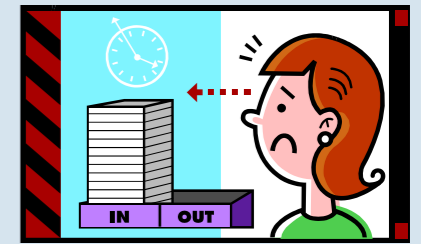


# Thresher addresses alarm triage in a particularly challenging domain.

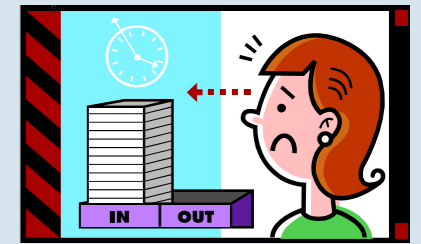




Manual triage is particularly hard for heap reachability reports.



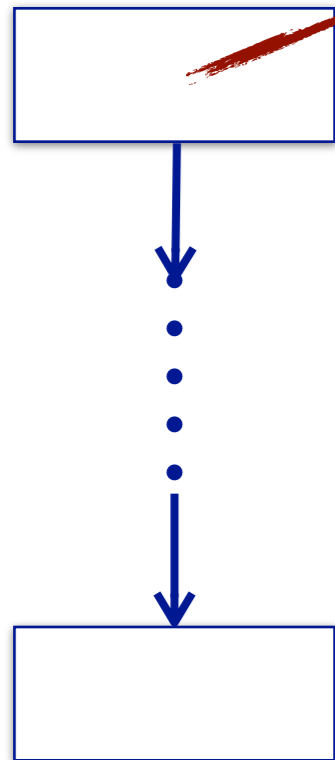
# Manual triage is particularly hard for heap reachability reports.



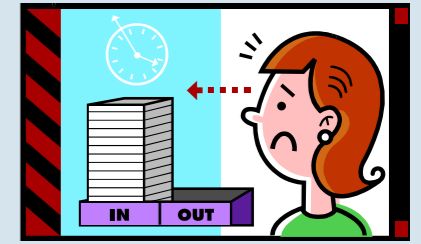
allocated here

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

MyClass1.java



# Manual triage is particularly hard for heap reachability reports.



allocated here



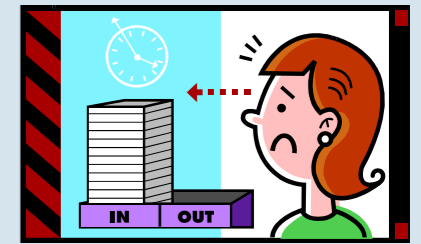
```
public class TcpClientSample
{
    public static void Main()
    {
        byte[] data = new byte[1024]; string input, stringData;
        TcpClient server;
        try{
            server = new TcpClient(" . . . . ", port);
        }catch (SocketException){
            Console.WriteLine("Unable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

MyC

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

LibraryClass1.java

# Manual triage is particularly hard for heap reachability reports.



allocated here



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

MyC

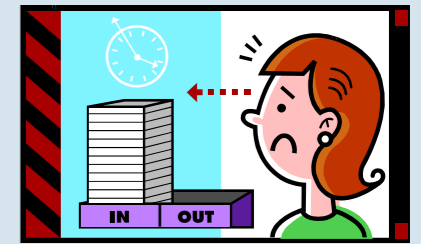
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public class TcpClientSample
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    public static void Main()
    {
        byte[] data = new byte[1024]; string input, stringData;
        TcpClient server;
        try{
            server = new TcpClient("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

Library

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

MyClass2.java

# Manual triage is particularly hard for heap reachability reports.



allocated here



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

MyC

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

Library

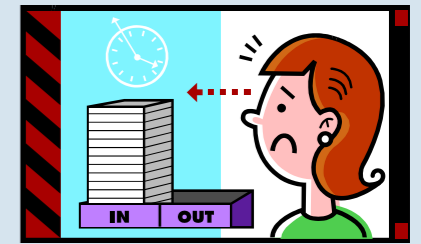
```
public class TcpClientSample
{
    public static void Main()
    {
        byte[] data = new byte[1024]; string input, stringData;
        TcpClient server;
        try{
            server = new TcpClient(" . . . . ", port);
        }catch (SocketException){
            Console.WriteLine("Unable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

MyC



Library2Class1.class

# Manual triage is particularly hard for heap reachability reports.



allocated here



```
public class TcpClientSample
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        byte[] data = new byte[1024]; string input, stringData;
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```

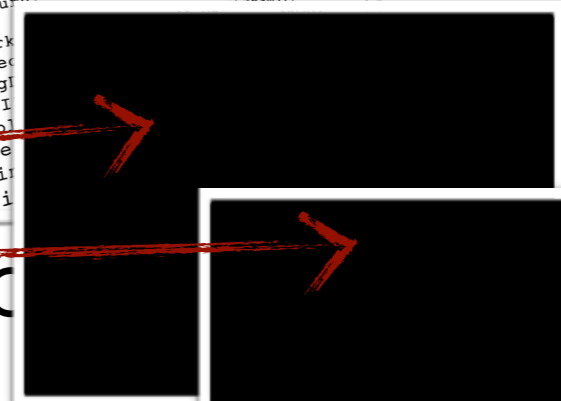
MyC

```
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        byte[] data = new byte[1024]; string input, stringData;
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            server = new TcpClient(" . . . . ", port);
        }catch (SocketException){
            Console.WriteLine("Unable to connect to server");
        }
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    }
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Network
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```

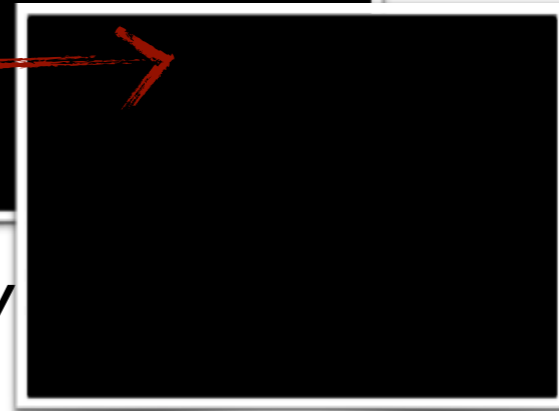
Library

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

MyC



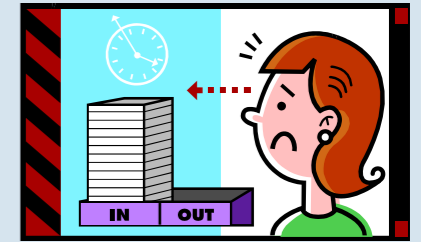
Library



java.util.HashMap.class



# Manual triage is particularly hard for heap reachability reports.



allocated here



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

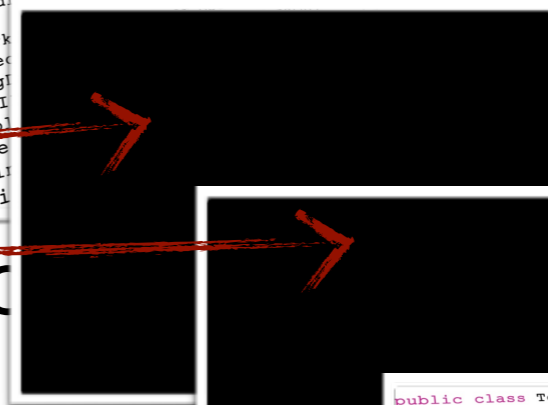
MyC

```
public class TcpClientSample
{
    public static void Main()
    {
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        return;
    }
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```

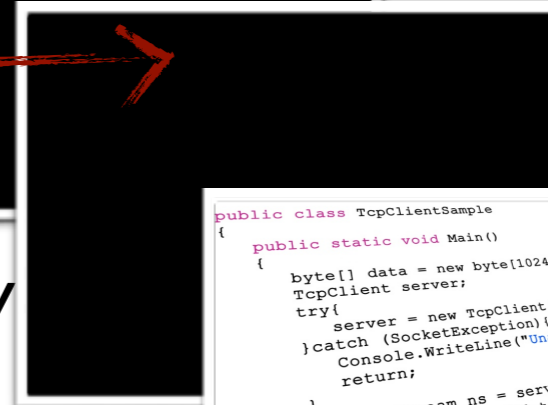
Library

```
public class TcpClientSample
{
    public static void Main()
    {
        byte[] data = new byte[1024]; string input, stringData;
        TcpClient server;
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        return;
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int rec
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Console
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```

MyC



Library

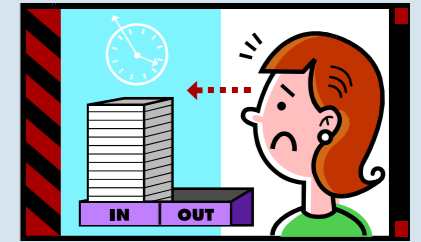


java.util.

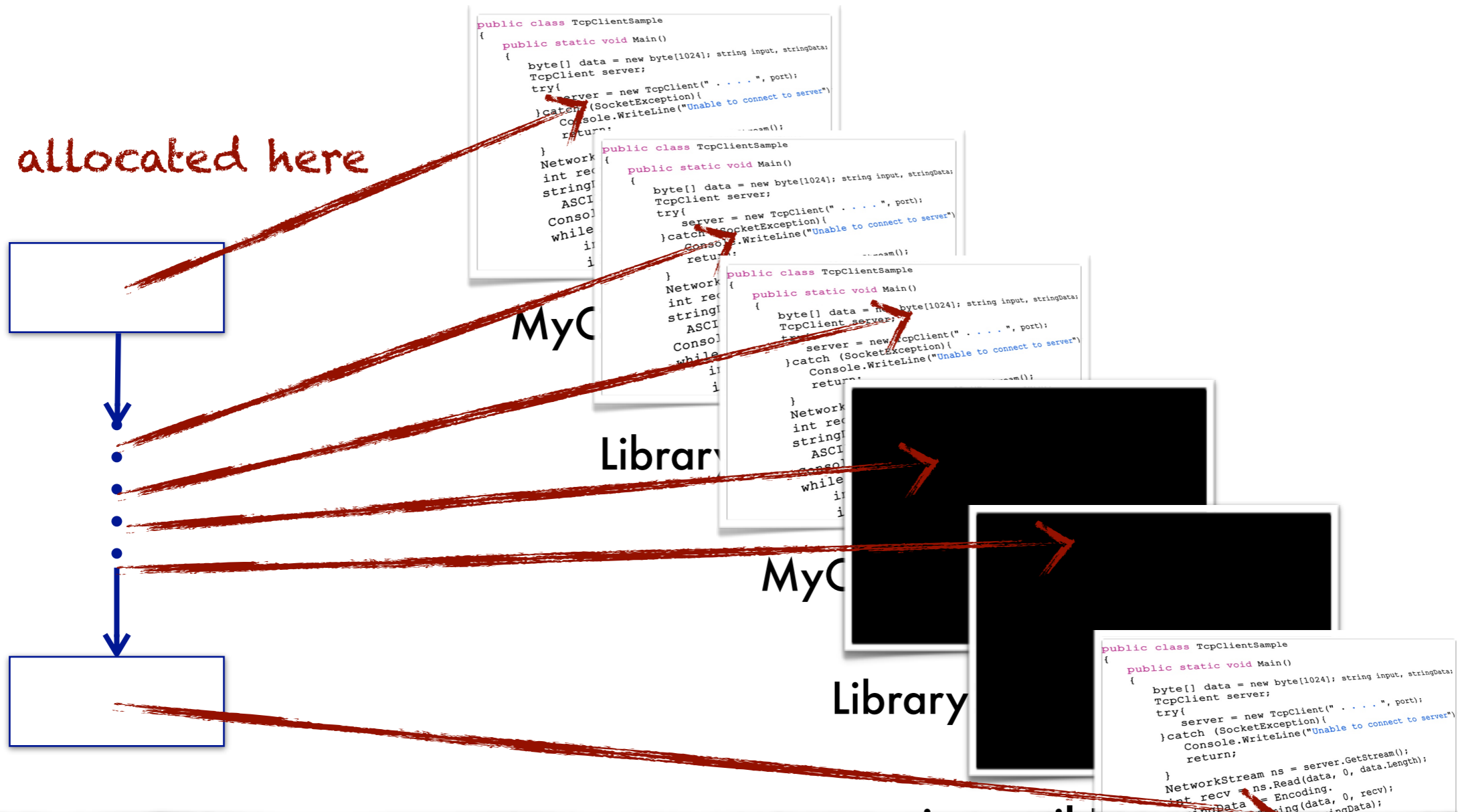
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    {
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        TcpClient server;
        try{
            server = new TcpClient(" . . . . ", port);
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            Console.WriteLine("Unable to connect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

MyClass3.java

# Manual triage is particularly hard for heap reachability reports.



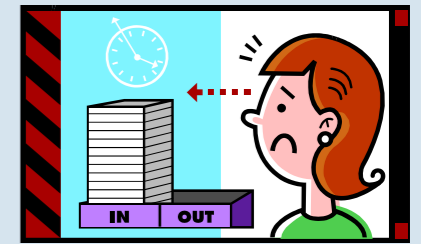
allocated here



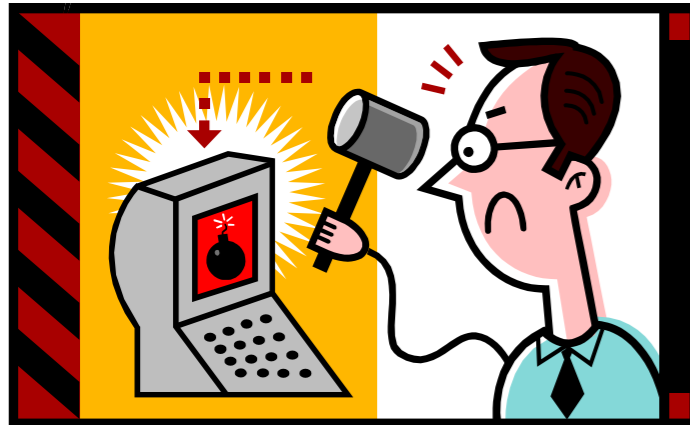
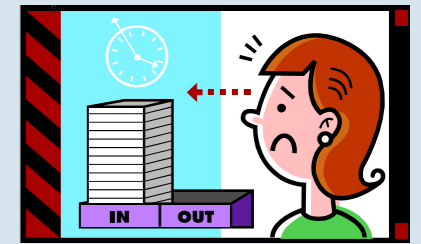
Get abstract heap path + maybe allocation sites  
Guesstimate: >1 to 2 hours per alarm to triage "well"



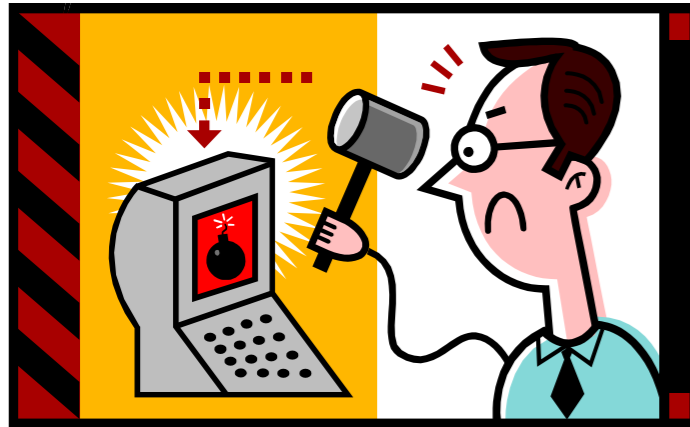
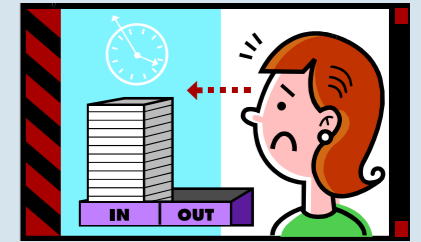
# Examining manual triage ...



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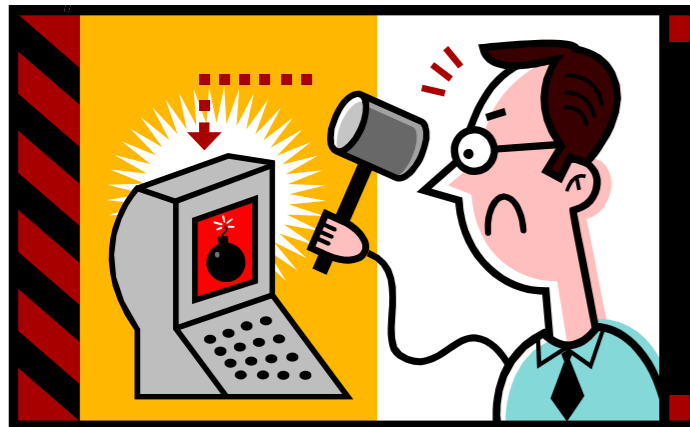
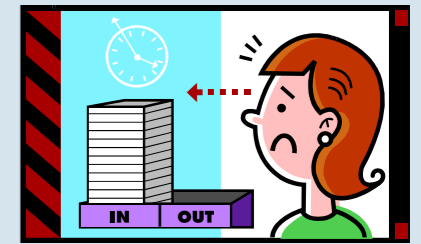


# Examining manual triage ...



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.

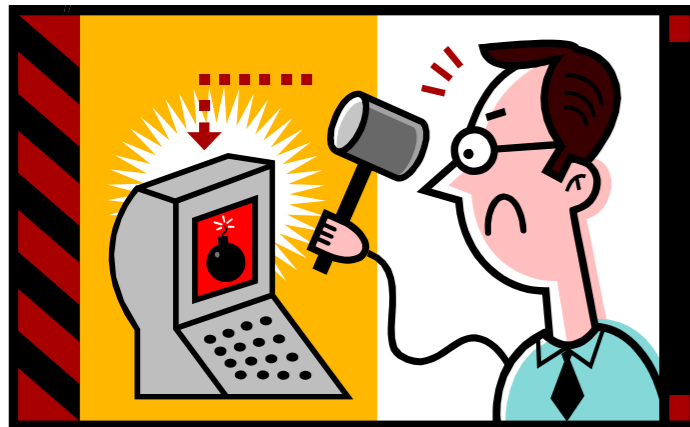
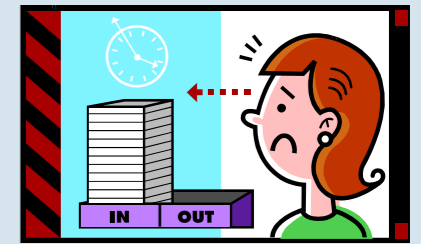
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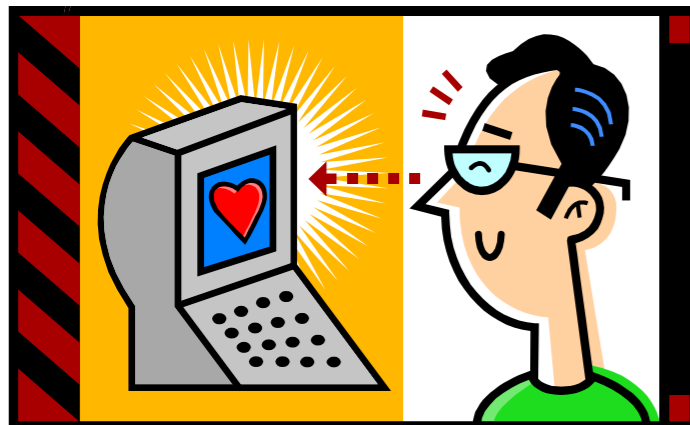
**We can do this with analysis!**

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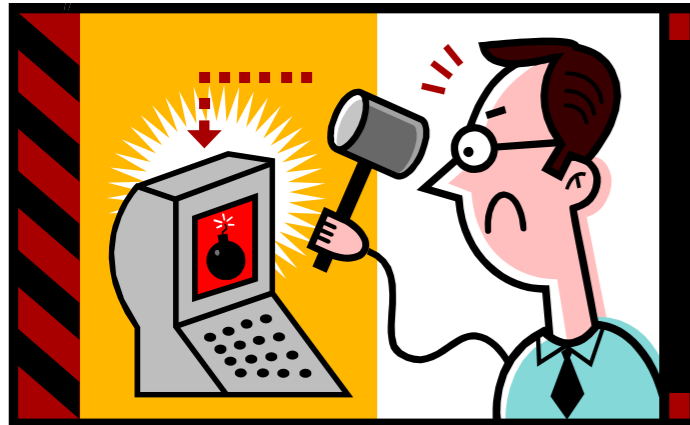
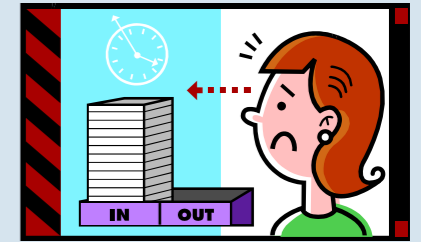


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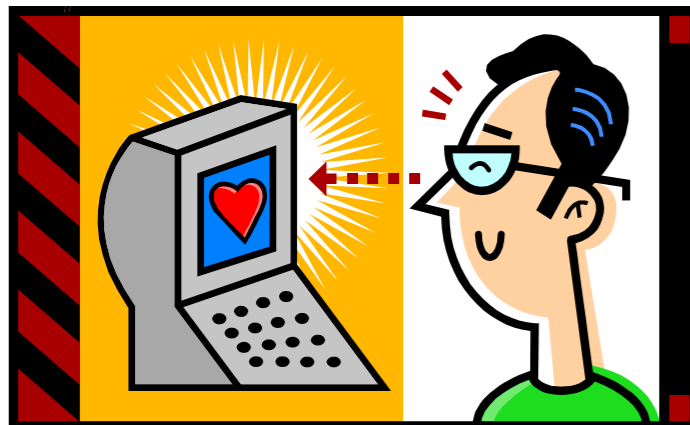


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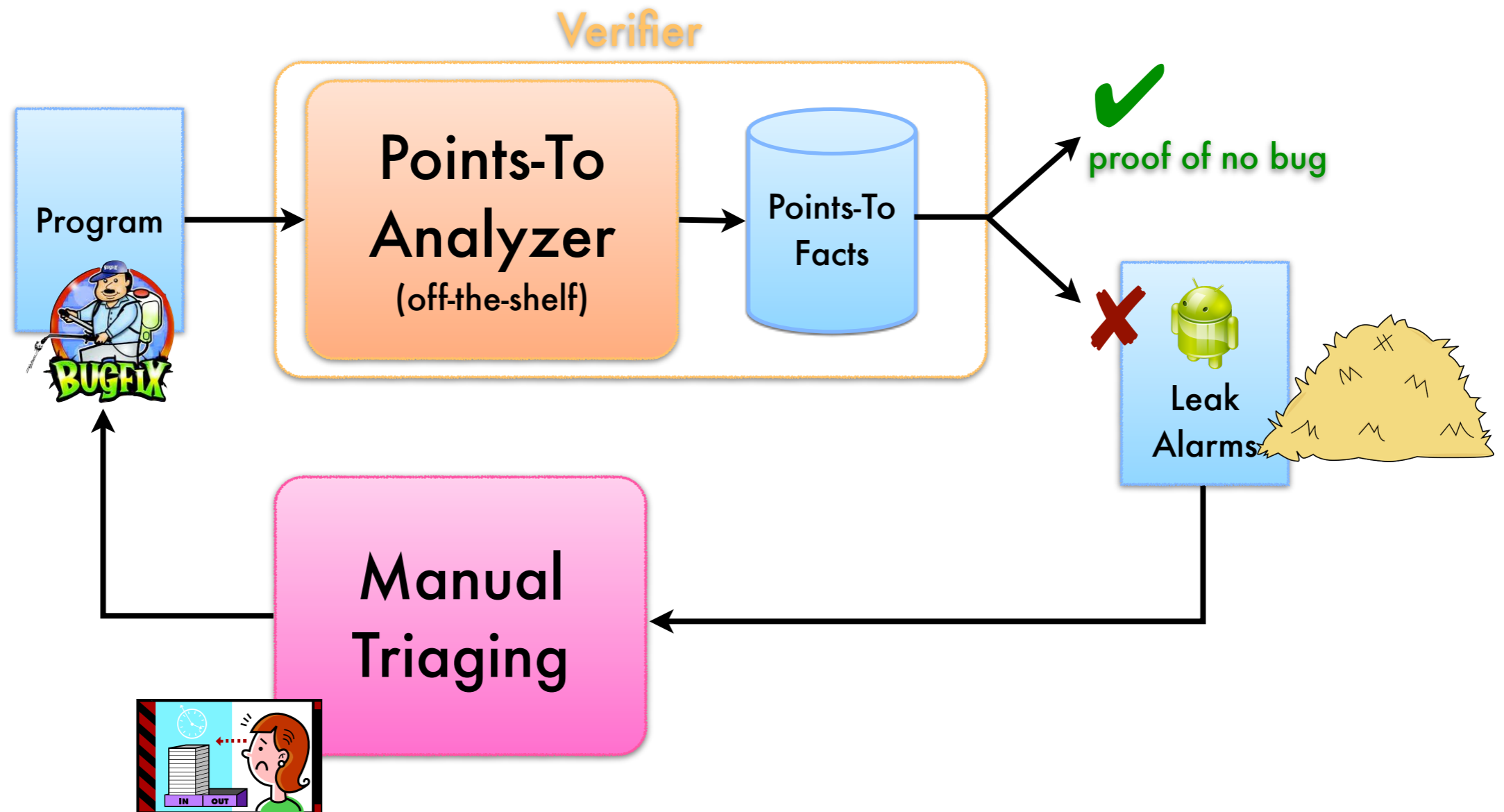
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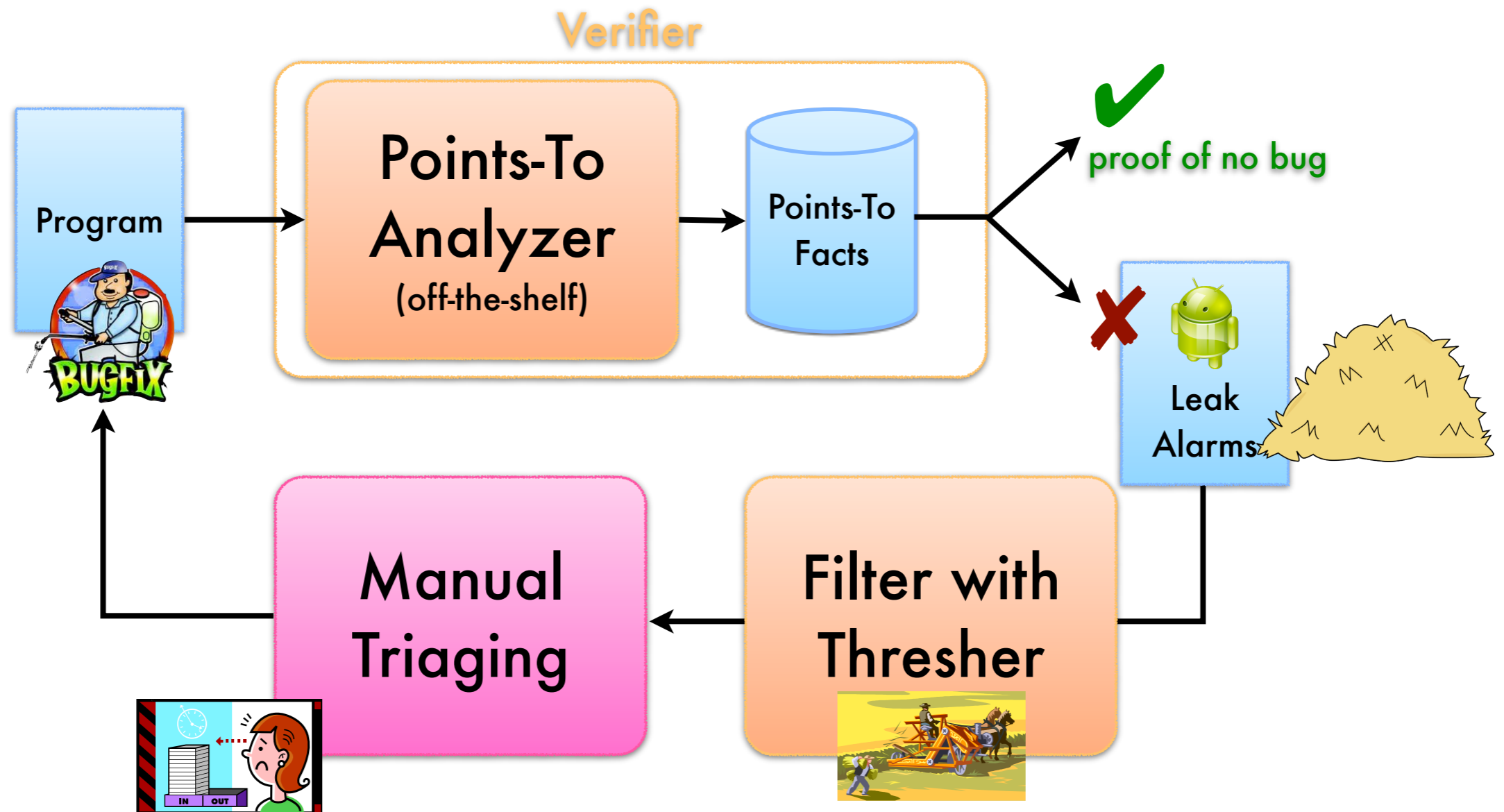


If we filter most false alarms, the user can triage more quickly and get to true bugs earlier (without frustration).

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

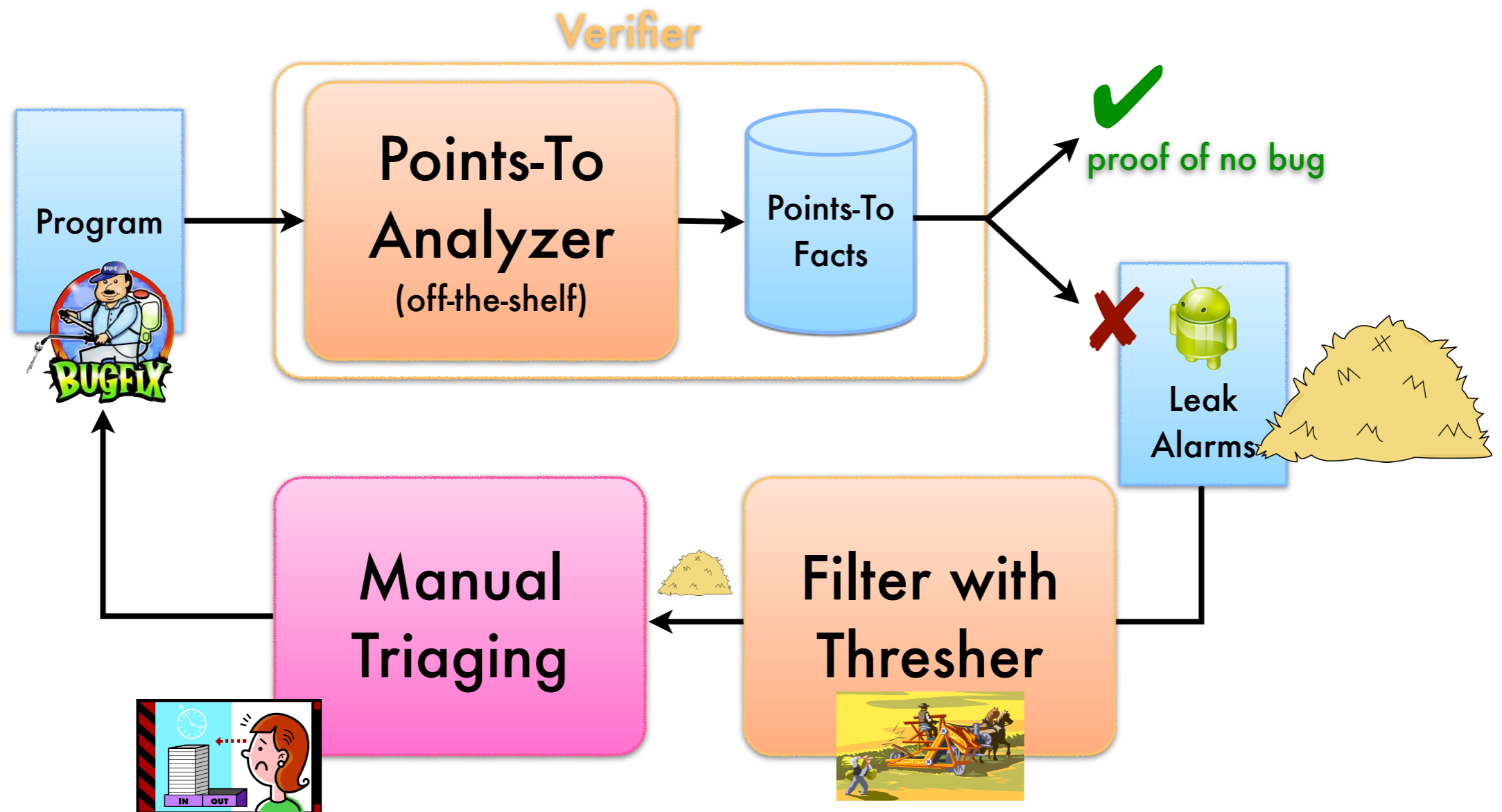


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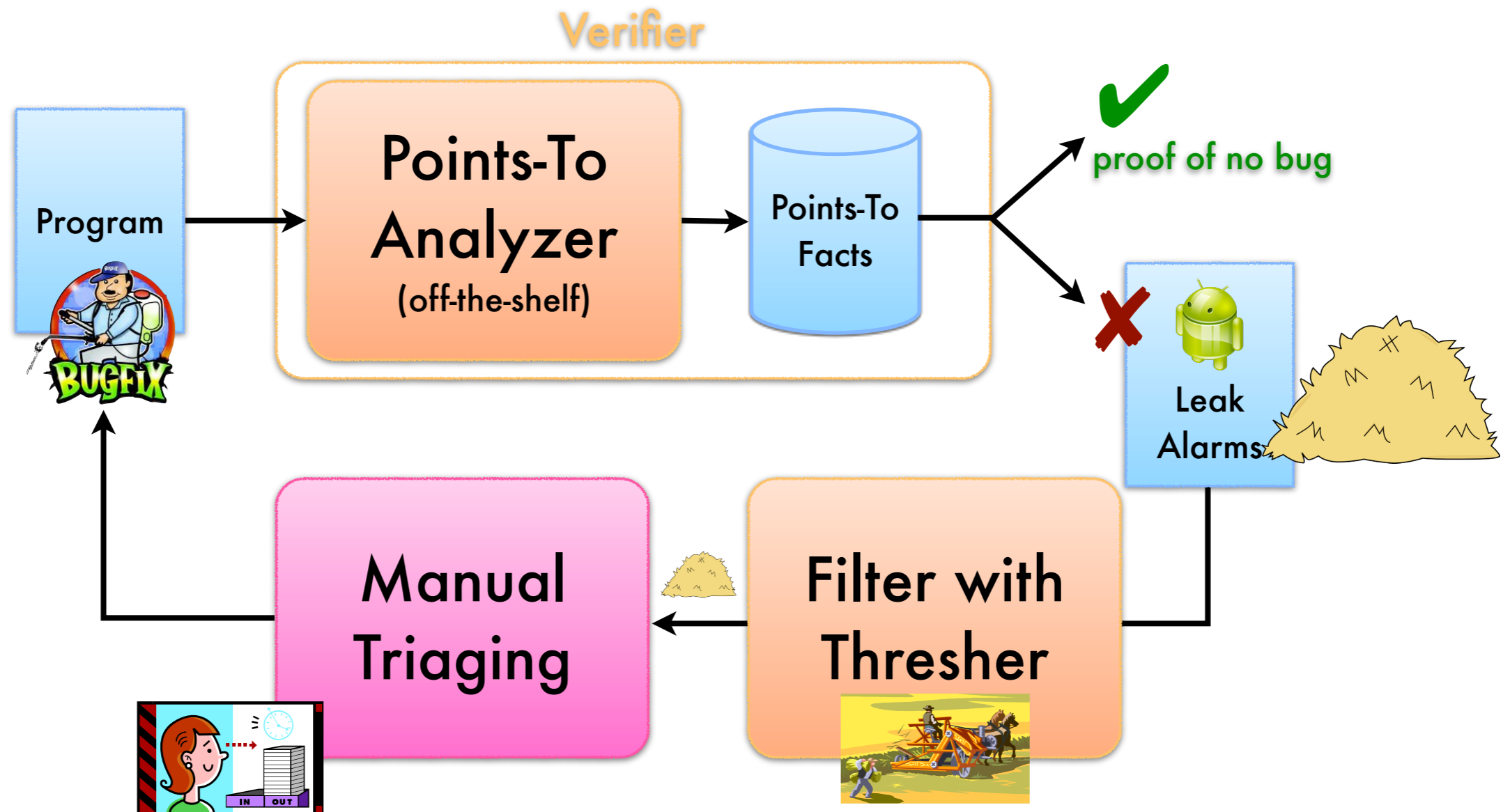




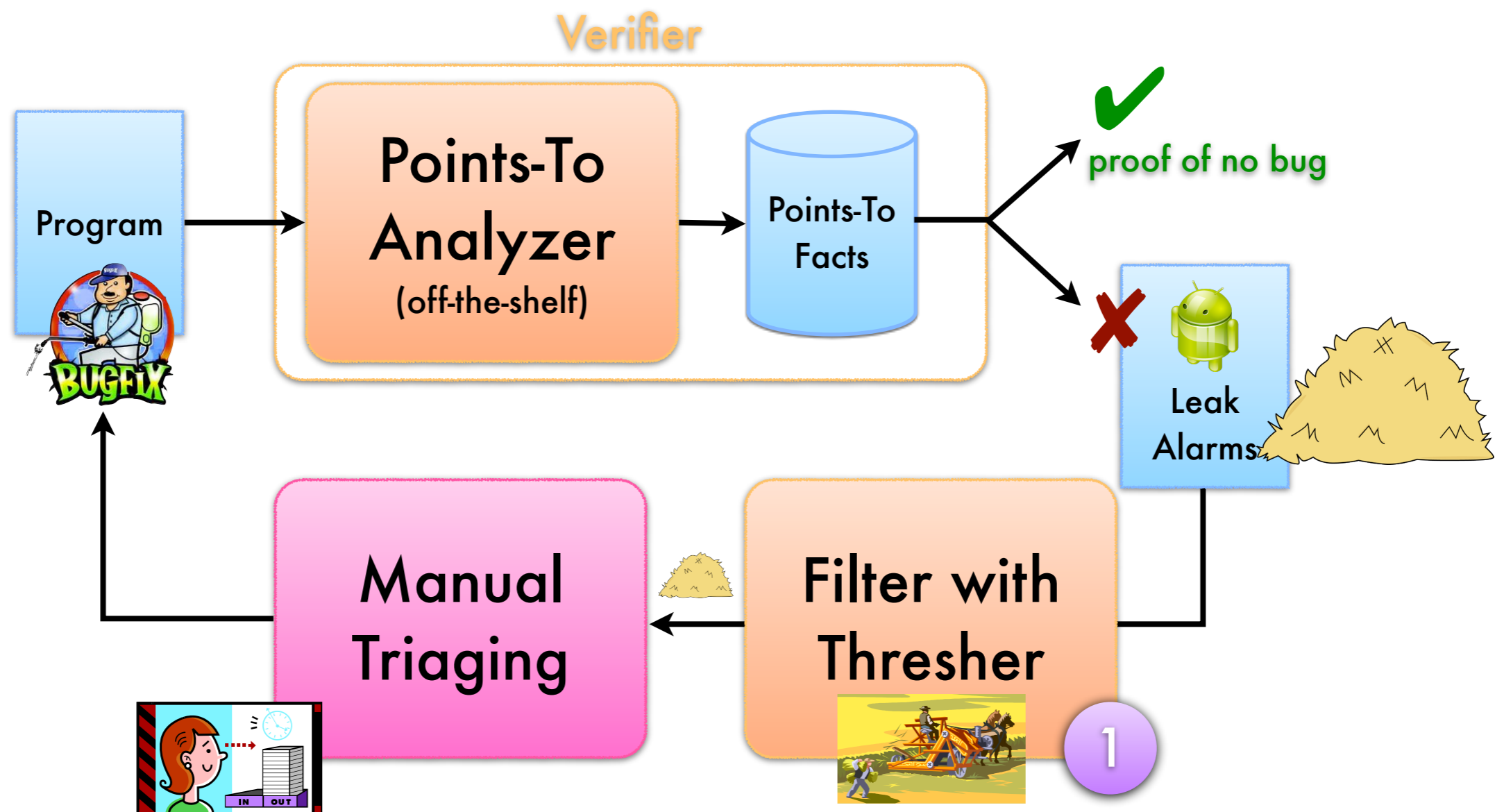
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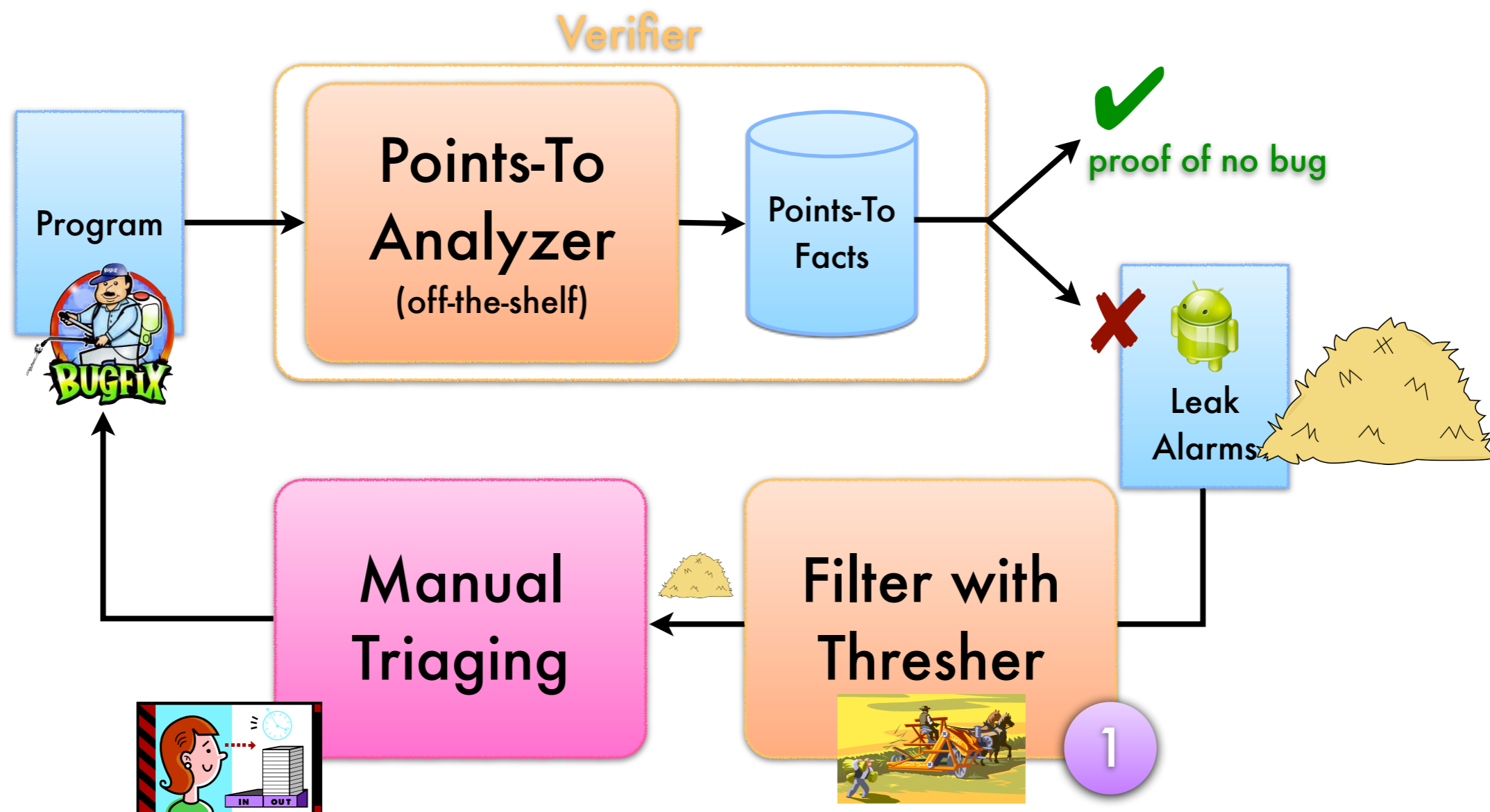


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Idea 1: Refute points-to on-demand with **second** “uber-precise” filter analysis

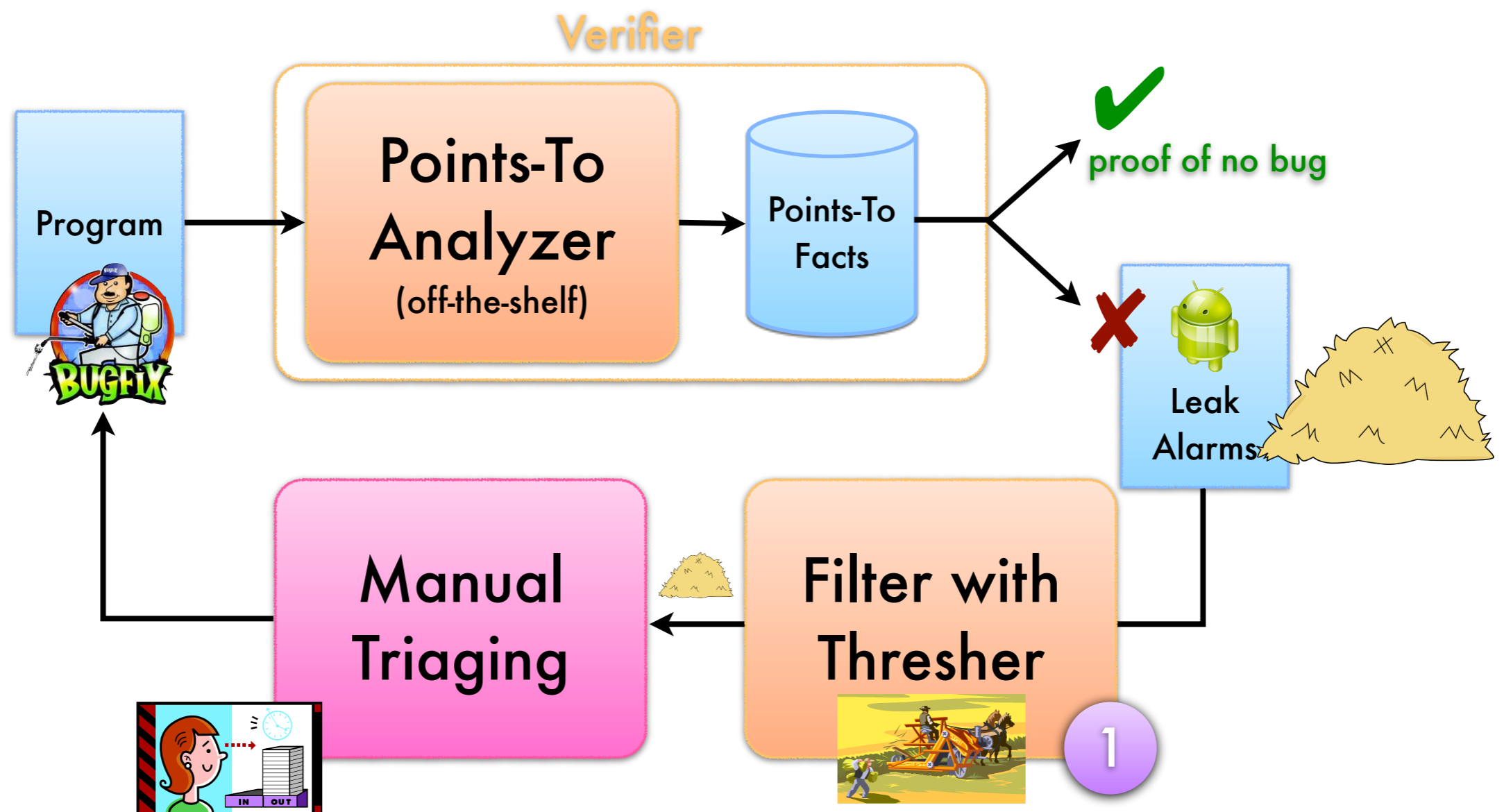
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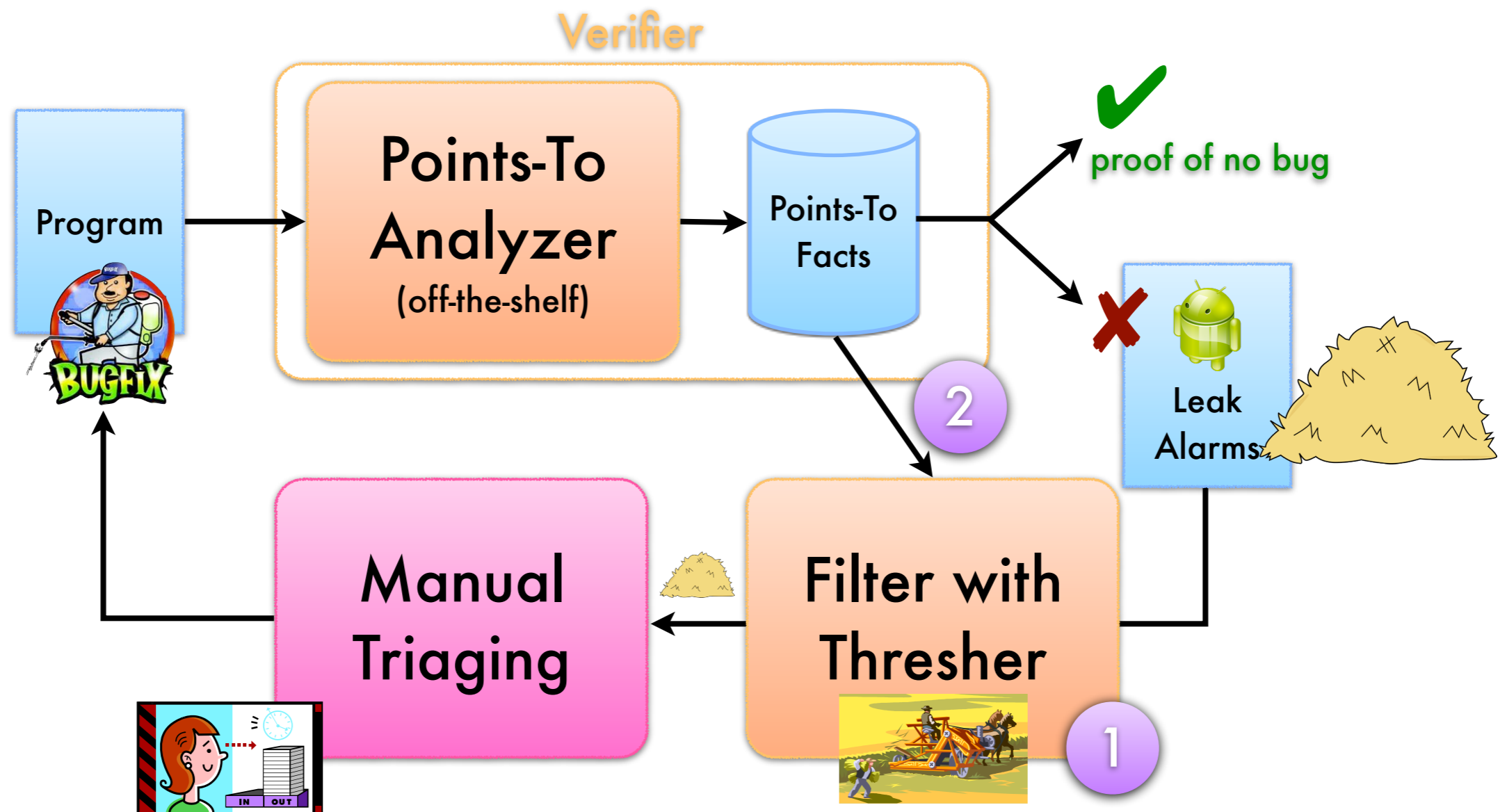
\*-sensitive

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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



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There **may** be an  
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$o$



$o'$



of type T .



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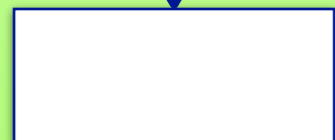
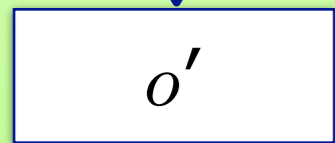
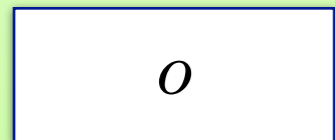
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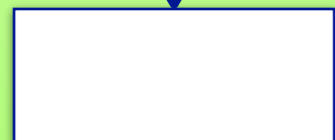
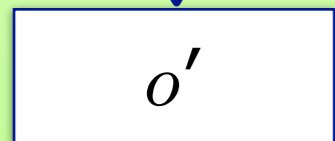
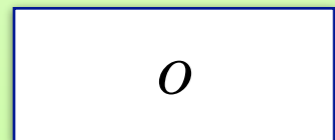
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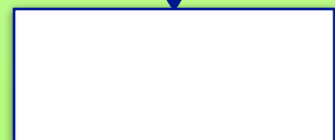
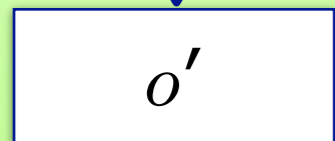
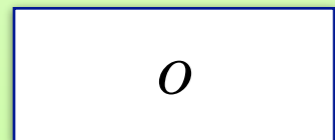
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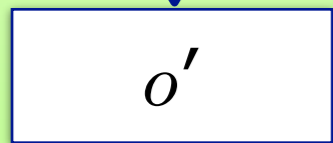
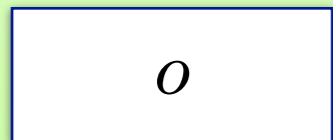
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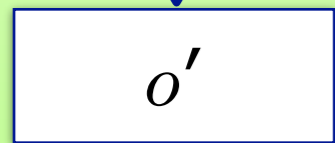
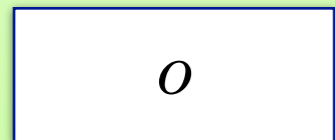
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# Refutation analysis is “Proof by Contradiction” with the “But Why?” game



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



**A** just asks “but why?”  
**B** reasons about program semantics

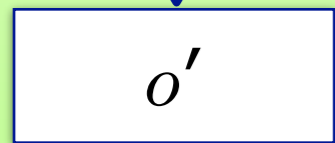
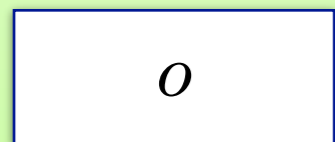
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Theorem: If **B** can't give an answer, contradiction.  
The alarm is false. It's been **refuted**. (**A** wins)



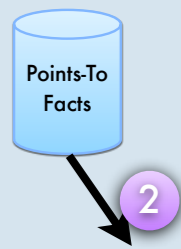
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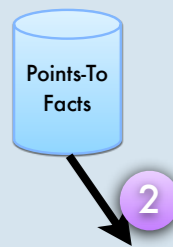


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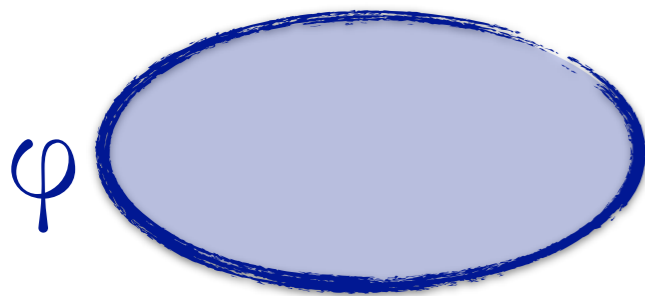
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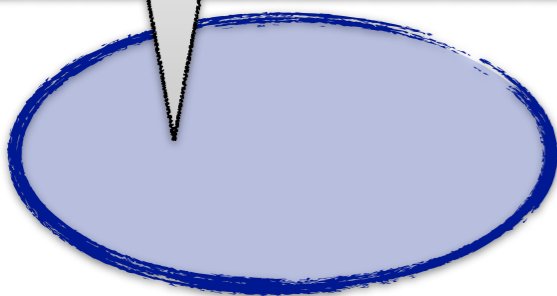
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set of possible states

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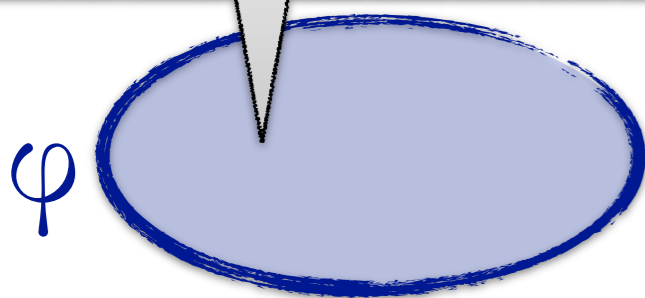
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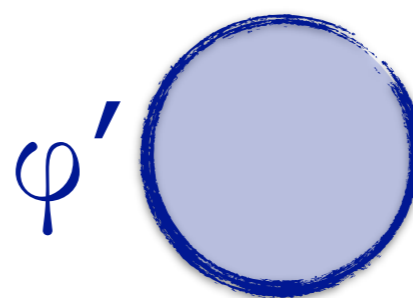
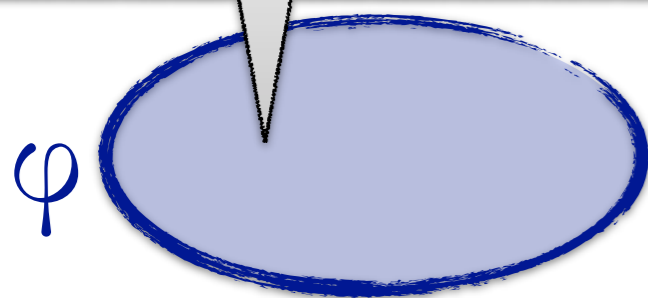
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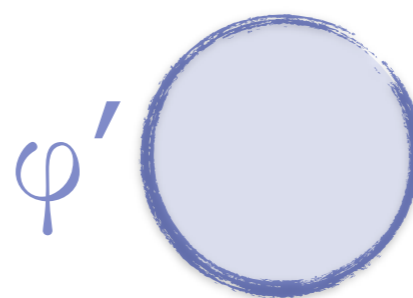
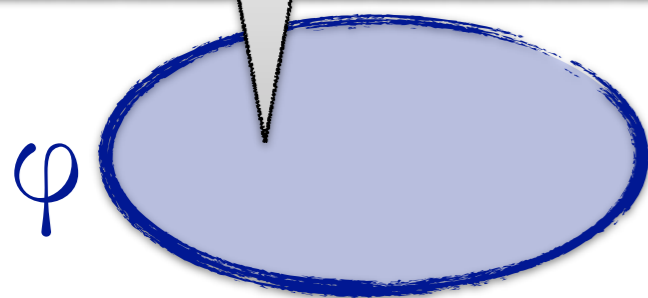
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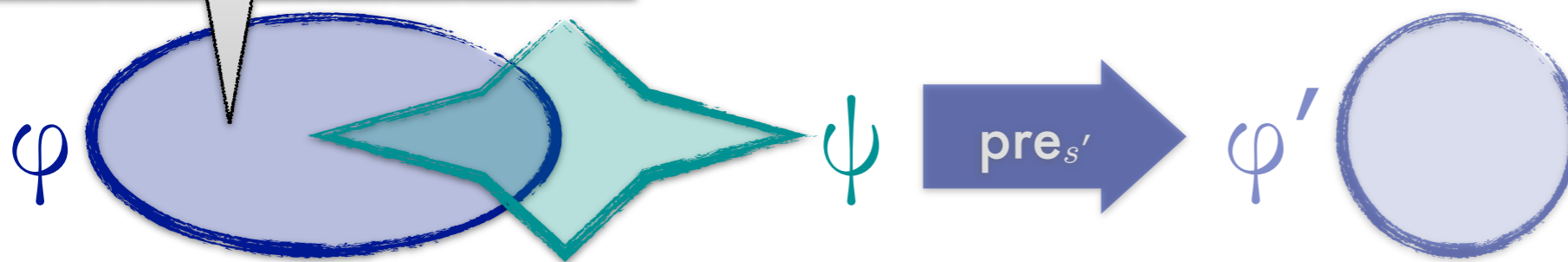
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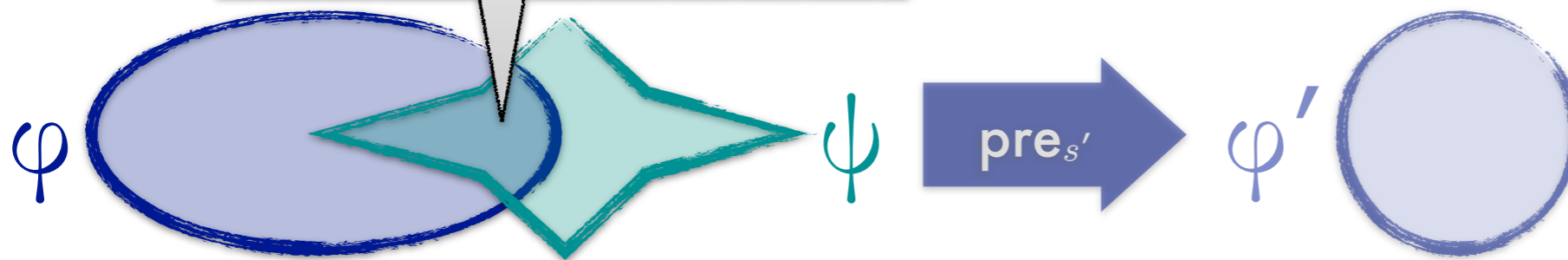
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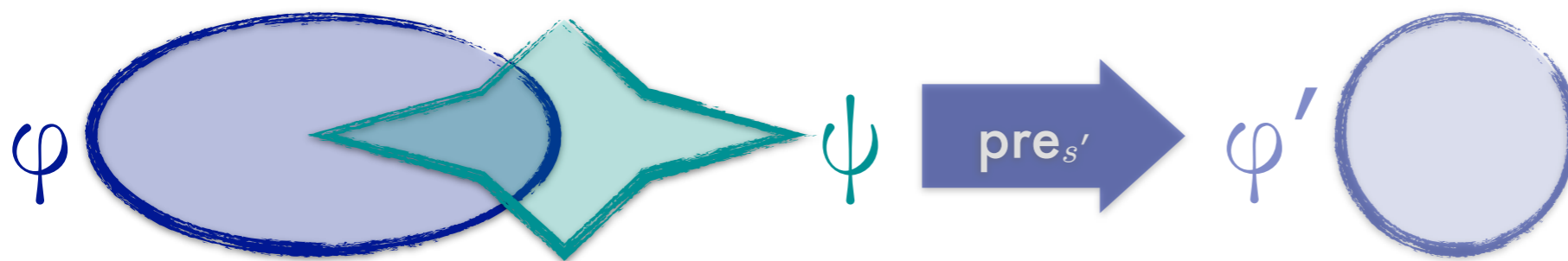


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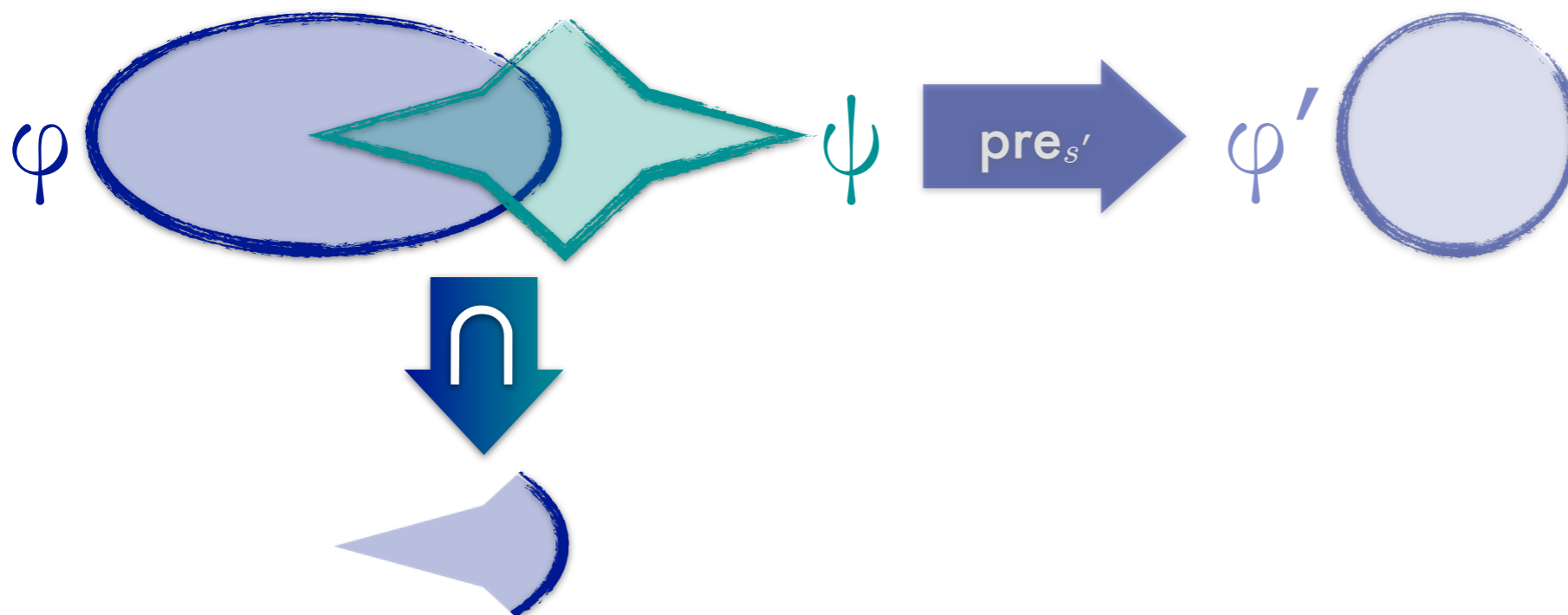


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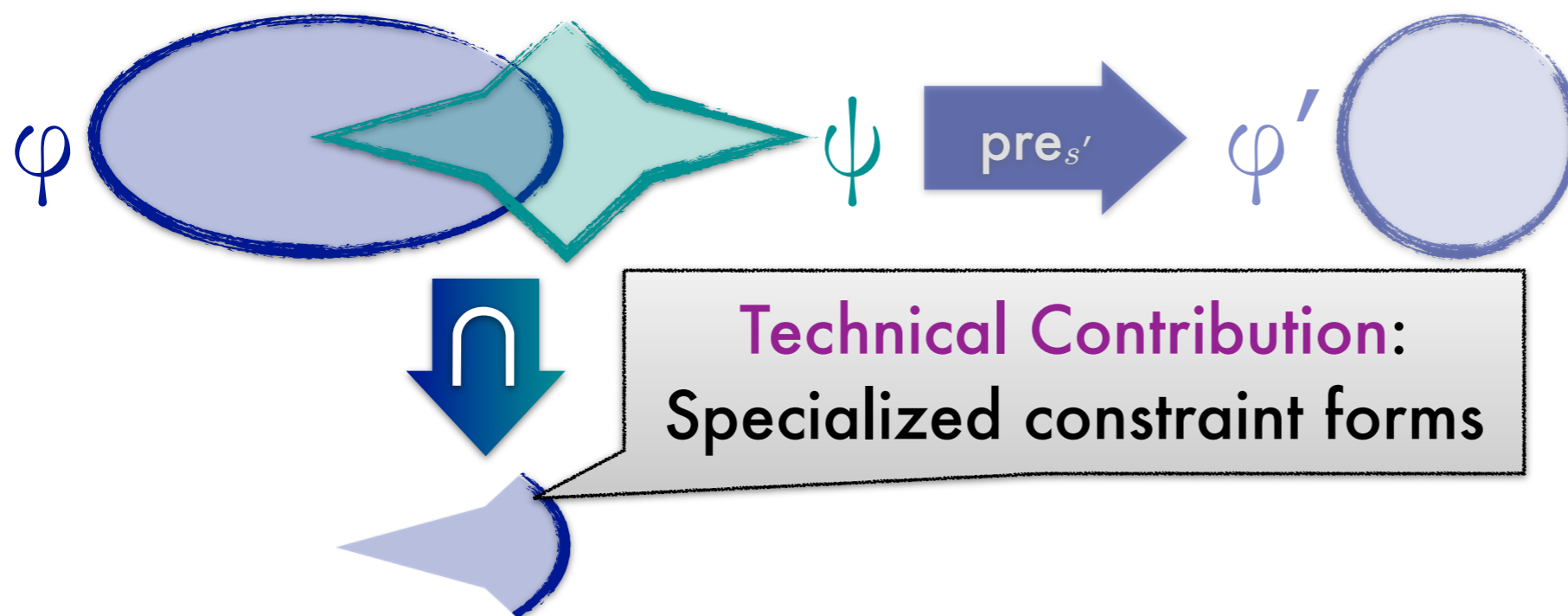


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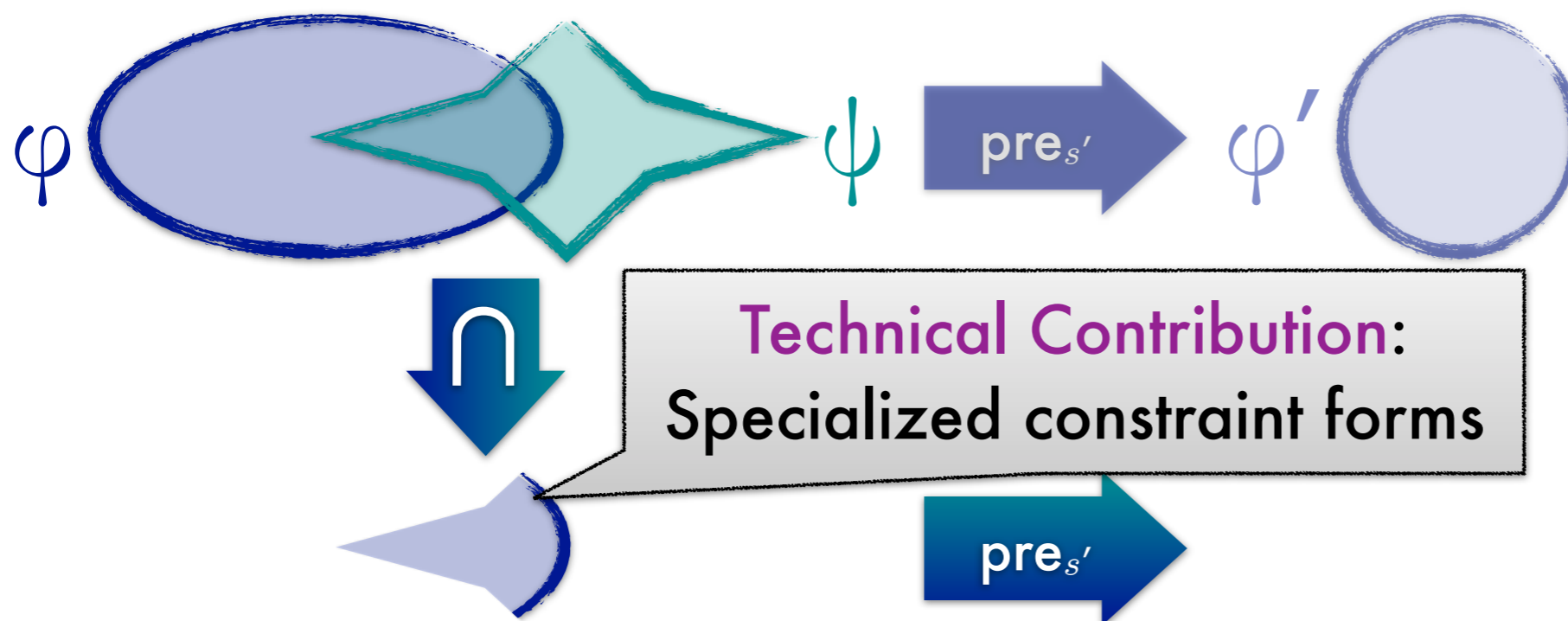


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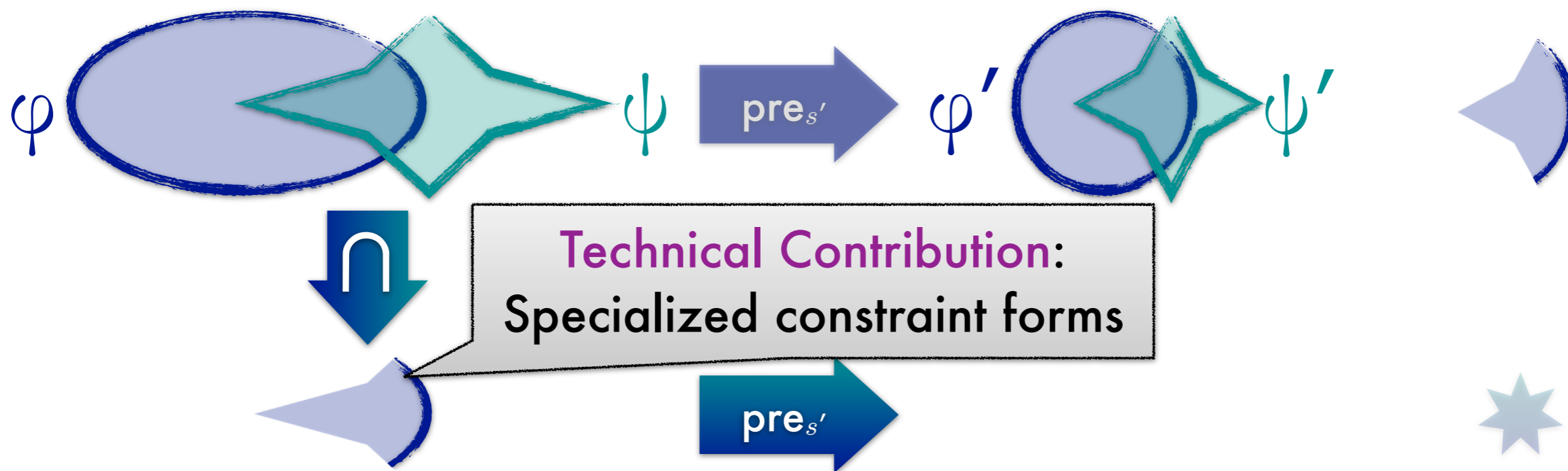


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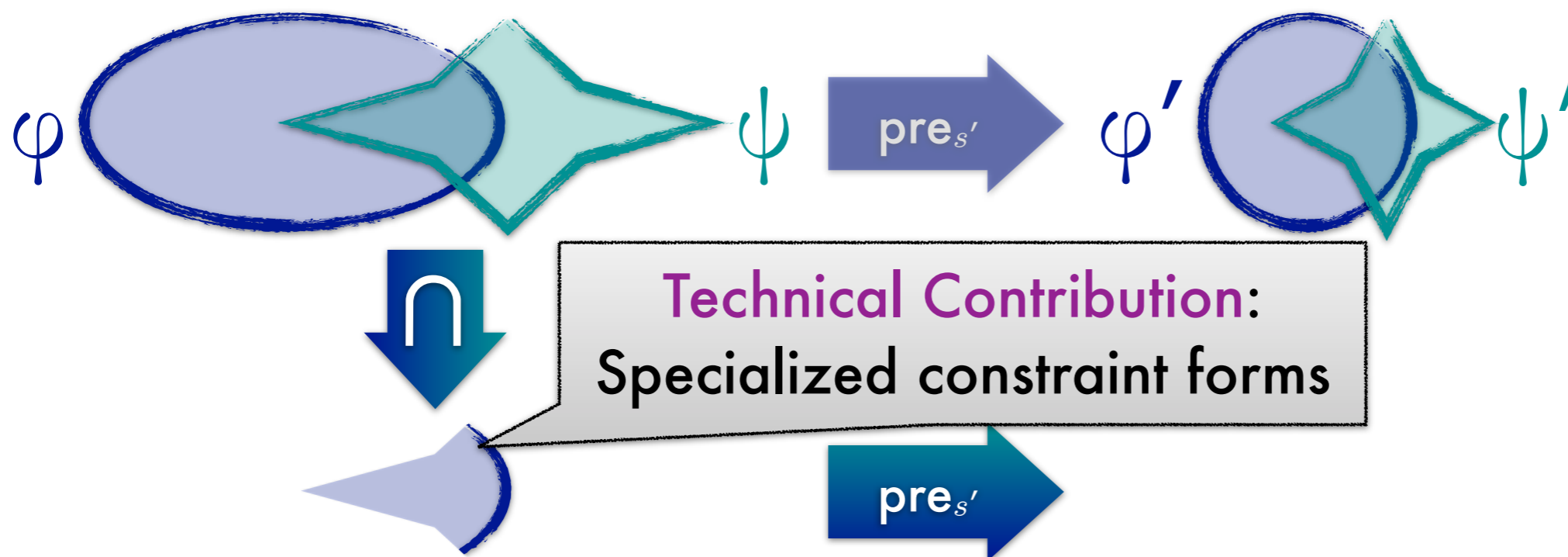


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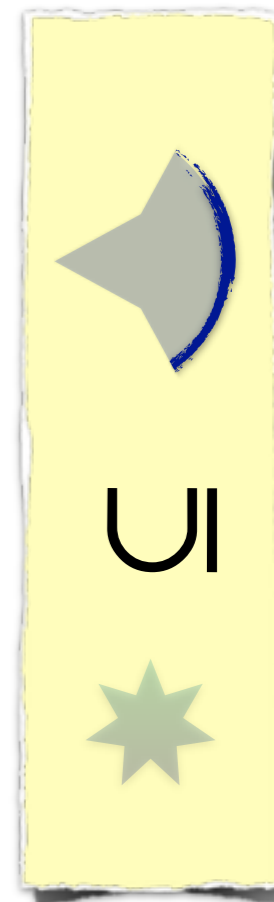
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**Technical Contribution:**  
Specialized constraint forms



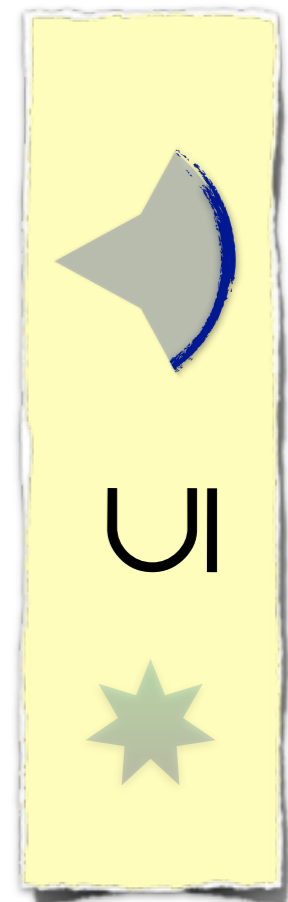
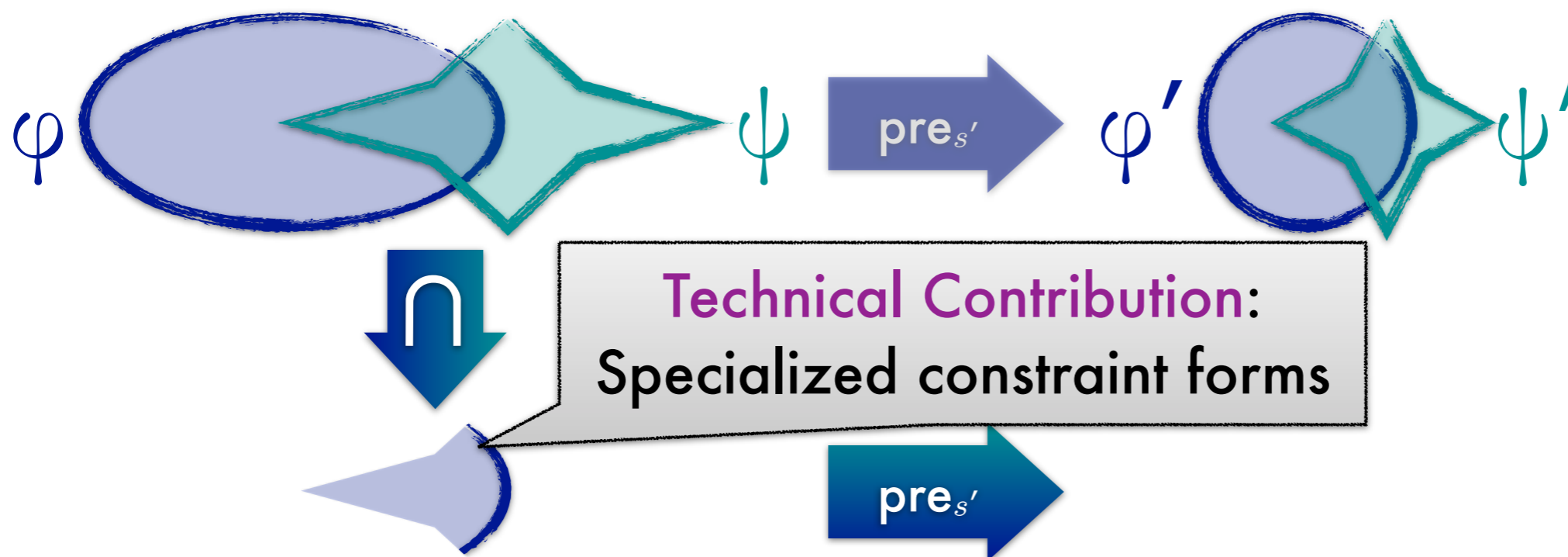
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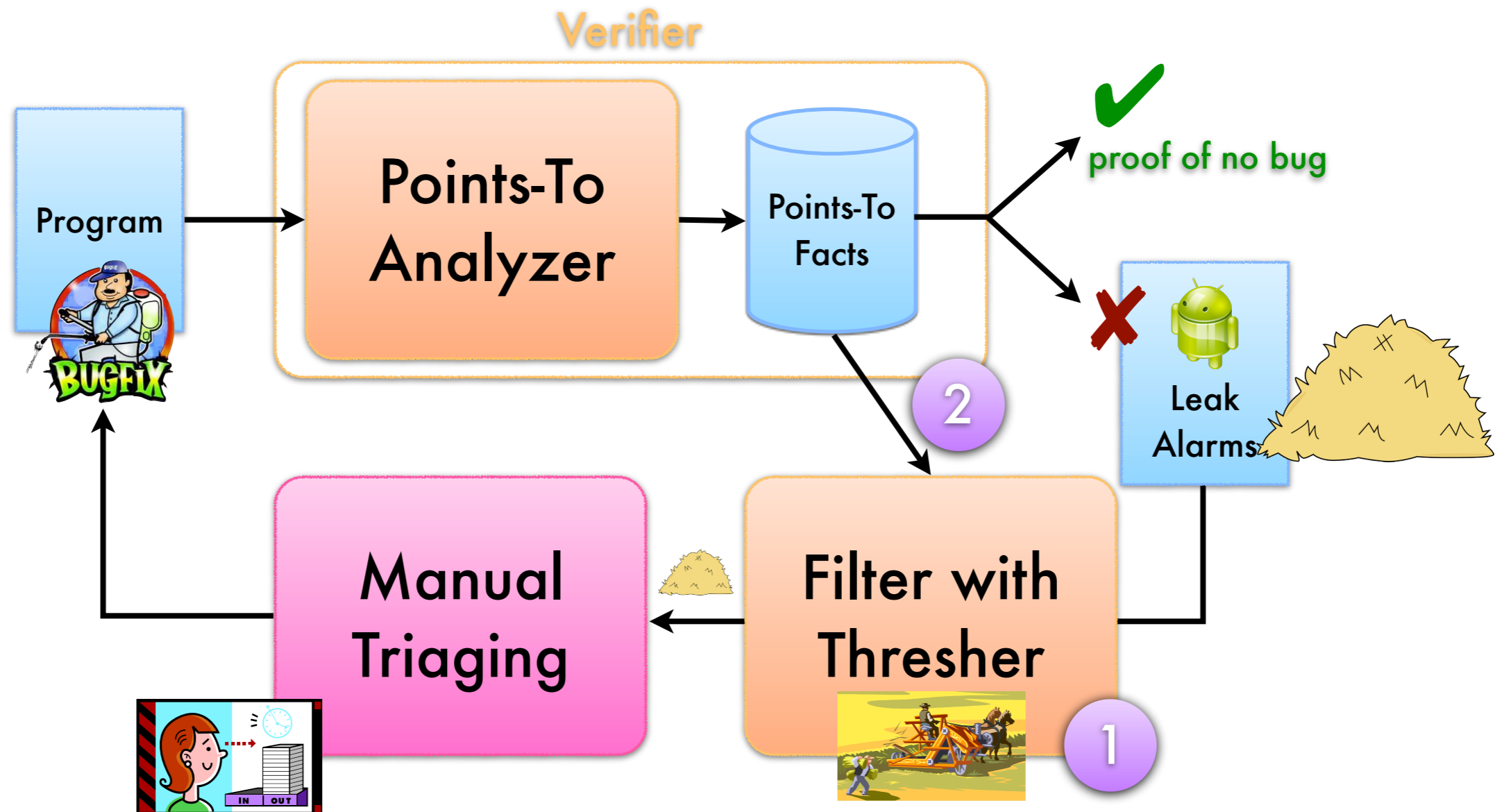
B. Because before the previous statement  $s'$ , the state could satisfy formula  $\varphi'$

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?

<b>Program</b>	<b>LOC</b>	<b>Points-To Alarms</b>	<b>Thresher Refuted</b>	<b>True Bugs</b>	<b>Thresher Time (s)</b>	<b>False Alarm %</b>	<b>Filtered %</b>
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<b>Total</b>	<b>72K</b>	<b>311</b>	<b>172</b>	<b>115</b>	<b>1602</b>	<b>17</b>	<b>88</b>

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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**



# Is Thresher effective at filtering?

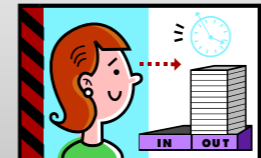
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staticfield-  
Activity pairs

Filtered



Manual





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aMetro	20K			36
K9Mail	40K			64
<b>Total</b>	<b>72K</b>			<b>115</b>

triage "well"  
at 10-15  
minutes per

staticfield-  
Activity pairs

Filtered



Manual



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< ~coffee to lunch break

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% after filtering

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

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



## Guesstimate

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

Triage "ok" without: ~30 hours

		Alerts	Rejected	Bugs	Time (s)	Alert %	ed %
PulsePoint	unknown	16	8	8	95	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

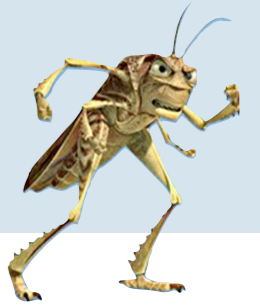
Android  
OS





**... in the process of finding leaks in apps**

# Find the Android's HashMap bug ...

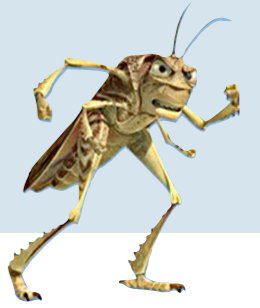


```
class HashMap {
    static Object[] EMPTY = new Object[2]; ...
    HashMap() { this.tbl = EMPTY; capacity initially empty }

    void put(Object key, Object val) {
        if (need capacity) {
            this.tbl = new Object[more capacity];
            copy from old table
        }
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    HashMap(Map m) {
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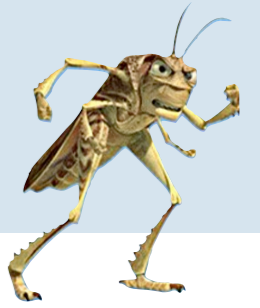


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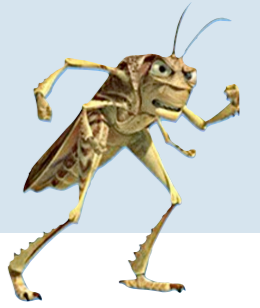
null object pattern: should not be written to

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allocate new  
backing array  
on first write

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

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}  
return "evil" content
```

return 0

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 ...

What if you store  
passwords in a HashMap?

```
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s  
H  
v  
}  
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this.tbl = EMPTY;

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copy from m

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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 ...

## What if you store passwords in a HashMap?

We reported this, Google fixed it

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

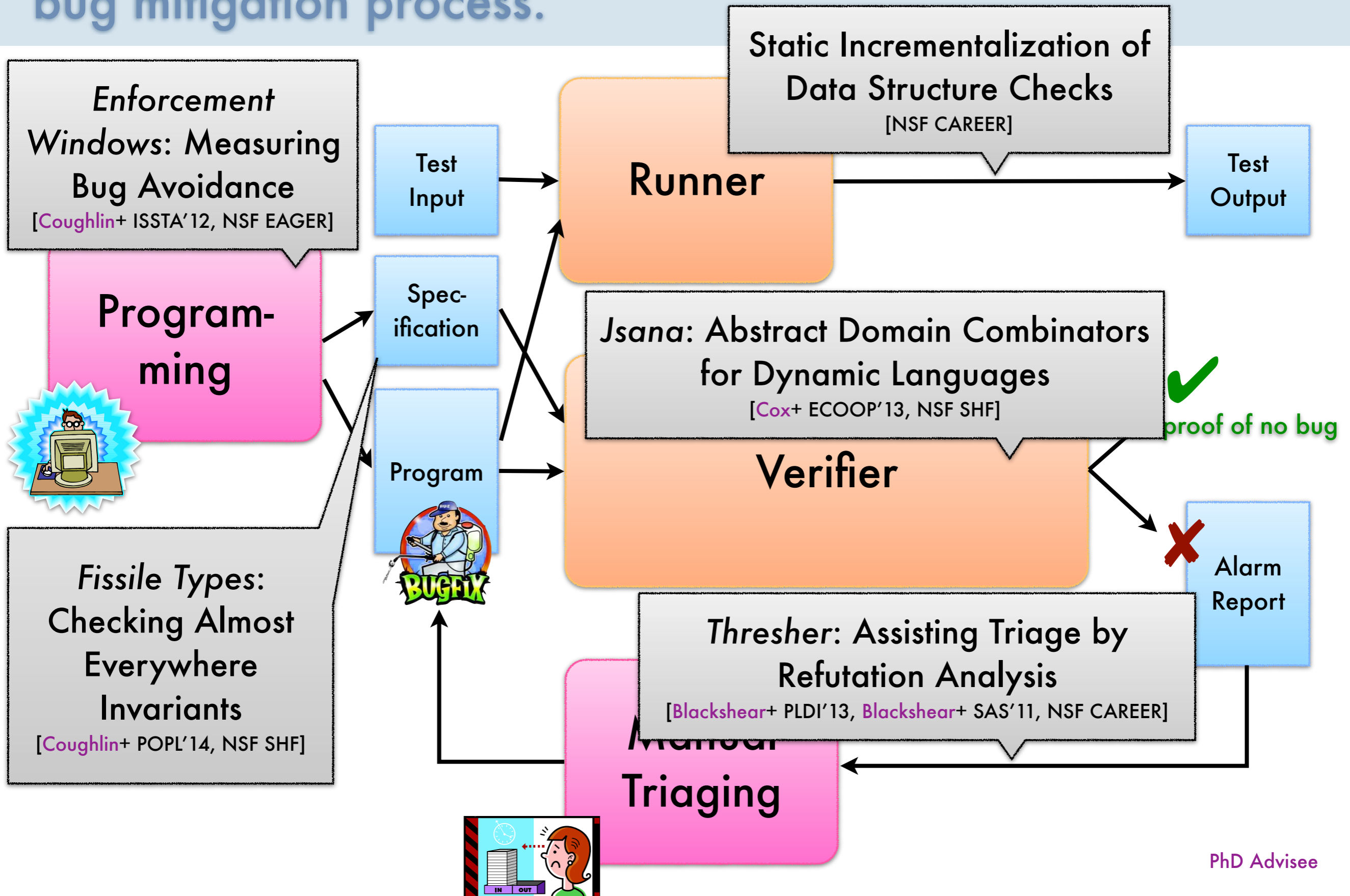


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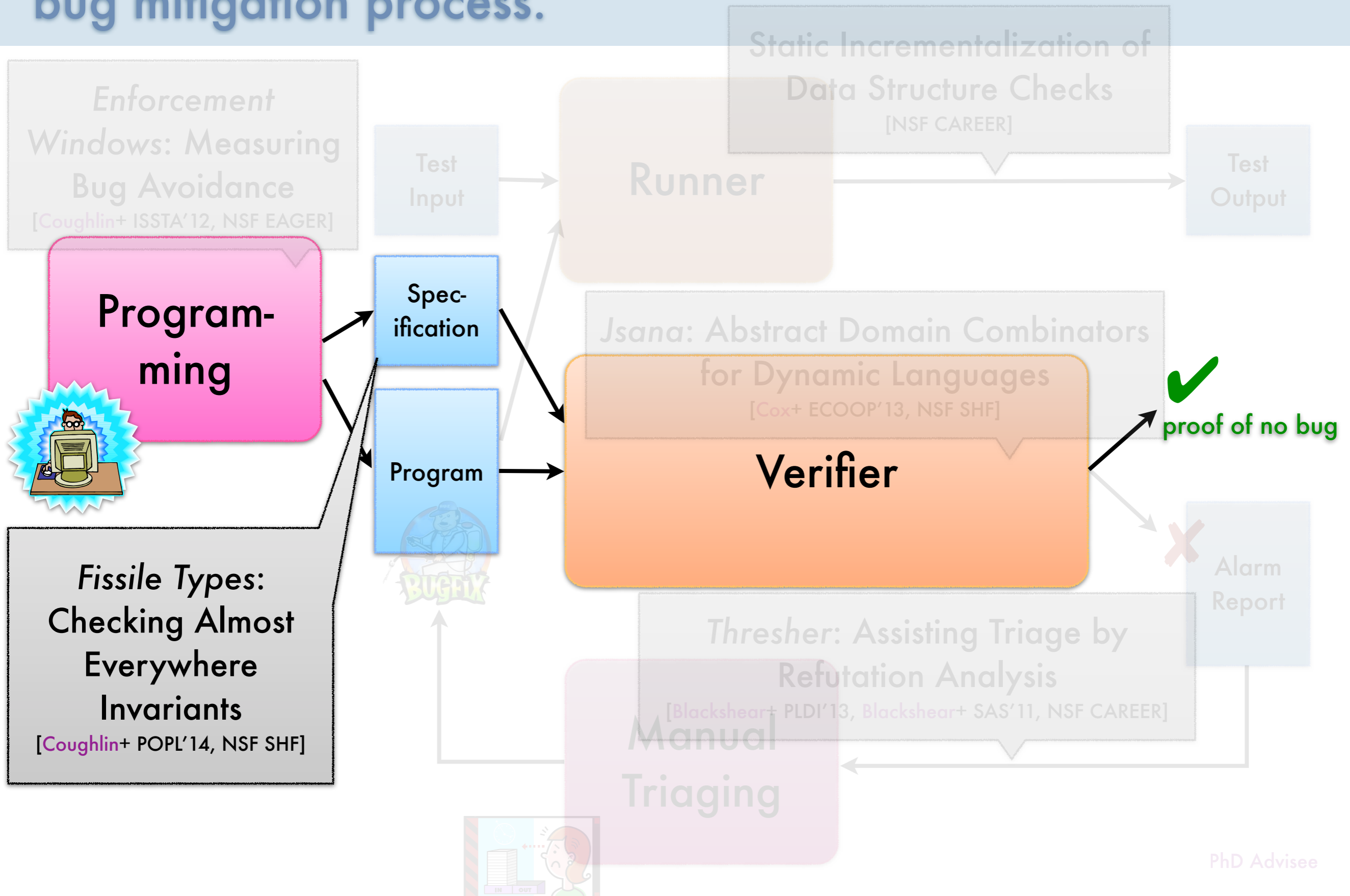
An "evil" implementation of the Map interface can corrupt EMPTY. Then, all HashMaps created in the future will be corrupted.

**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] ()
```

# Method Reflection and the Great Divide

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

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"web 2.0" developers



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Type system designers **worry**.

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

# Method Reflection and the Great Divide

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

`object [string] ()`

type system designers



Type system designers **worry**.

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

"web 2.0" developers



"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**.

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

When  
obj  
by

**"MethodNotFound" checked at run time**

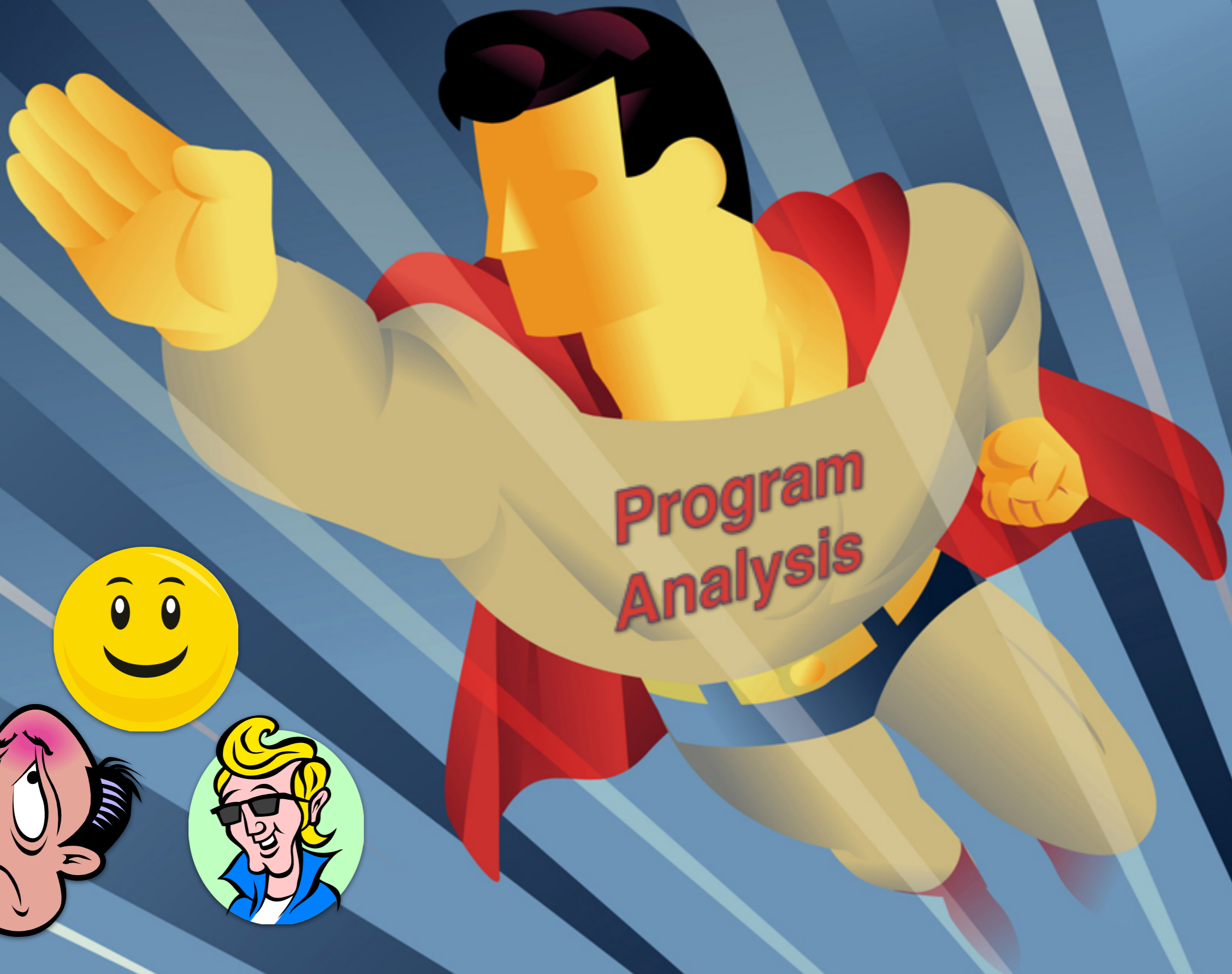
**static safety.**



**Program  
Analysis**







**Program  
Analysis**



Programs are often

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

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Program

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```
callback.o [callback.m] ()
```

Program

Programs are often

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

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

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*invariant holds*

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but only temporarily



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invariant broken



but only temporarily



Program

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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Proved **86%** of check sites (up from 76%) at  
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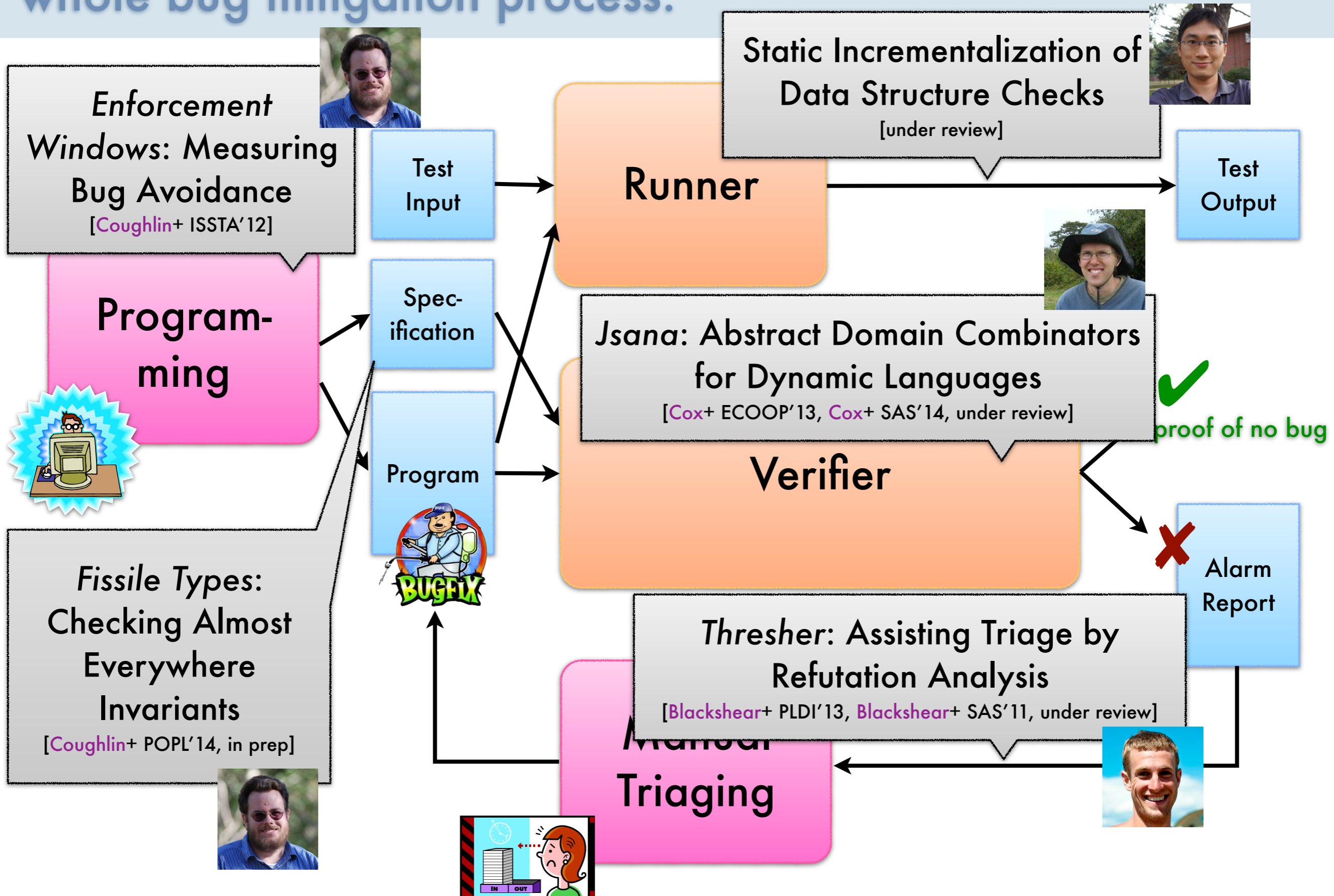
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**Big Deal: makes IDE integration possible**



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





[www.cs.colorado.edu/~bec](http://www.cs.colorado.edu/~bec)  
[pl.cs.colorado.edu](http://pl.cs.colorado.edu)



[www.cs.colorado.edu/~bec](http://www.cs.colorado.edu/~bec)  
[pl.cs.colorado.edu](http://pl.cs.colorado.edu)



Cerny



Chang



Sankaranaryananan



Somenzi