Static Automated Program Repair for Heap Properties

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Software Quality in Real Evolving Systems

isr institute for SOFTWARE RESEARCH

Motivating Example

A bug in error-prone

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```
public class GuardedByBinder {
   case IDENTIFIER: {
      Symbol.MethodSymbol method =
        context.resolver.resolveMethod(node, identifier.getName());


      return bindSelect(computeBase(context, method), method);
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}
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}
```

"method" can be null

A bug in error-prone

Motivating Example

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   case IDENTIFIER: {
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Fixed + Test Added

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public static void checkGuardedBy(boolean condition, String message) {
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Fixed + Test Added

Same issue!

A bug in error-prone

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Fixed + Test Added

Fixed 18 months later!

What We Do

What We Do

- Local reasoning

What We Do

- Local reasoning of program fragments

What We Do

- Local reasoning of program fragments

for Program Repair!

A bug in error-prone

Motivating Example

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Local semantic effects

Fixed 18 months later!

A bug in error-prone

Motivating Example

```
public class GuardedByBinder {
   case IDENTIFIER: {
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Local semantic effects

Pre & Postconditions

Fixed 18 months later!

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Local semantic effects

Pre & Postconditions

A bug in error-prone

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Local semantic effects

Pre & Postconditions

A bug in error-prone

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```

Local semantic effects

Pre & Postconditions

Right now.

What We Do

- Local reasoning of program fragments

for Program Repair!

What We Do

- Local reasoning of existing program fragments

for Program Repair!

What We Do

- Local reasoning of program fragments

for Program Repair!

What We Do

- Local reasoning of program fragments

for Program Repair!

No tests

What We Do

- Local reasoning of program fragments

for Program Repair!

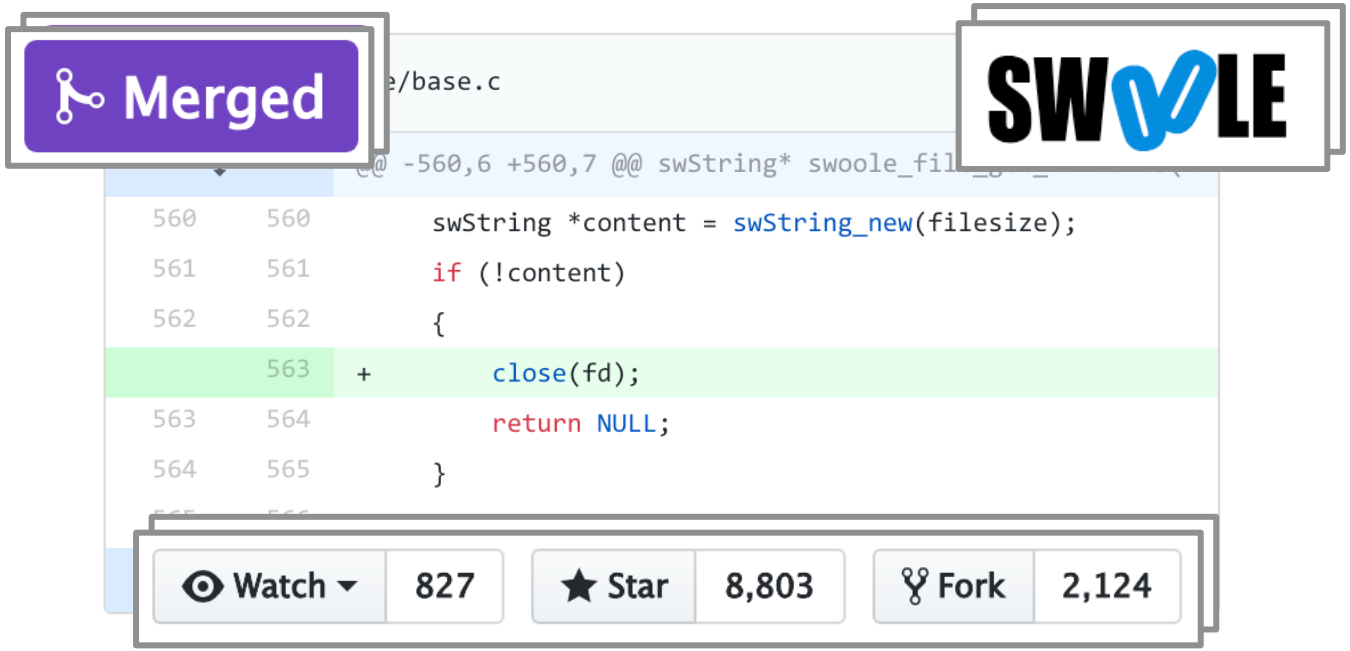
No tests

Real programs

What We Do

- Local reasoning of program fragments

for Program Repair!



What We Do

- Local reasoning of program fragments

for Program Repair!

- Heap defects
  - Resource Leaks
  - Memory Leaks
  - Null dereferences

What We Do

- Local reasoning of program fragments

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Pre/Post fix specification

What We Do

- Local reasoning of program fragments

for Program Repair!

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Separation Logic

Static Analysis with Separation Logic

Static Analysis with Separation Logic

- Separation Logic reasons about heap state

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Static Analysis with Separation Logic

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- Bug types
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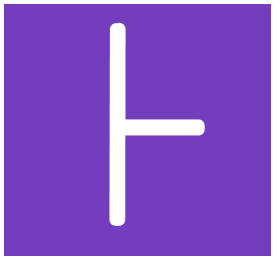

Static Analysis with Separation Logic

- Separation Logic reasons about heap state

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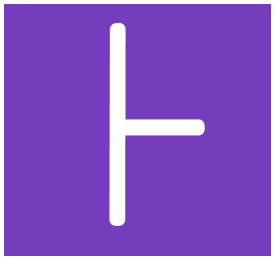

- C/C++, Java, Objective C

Static Analysis with Separation Logic

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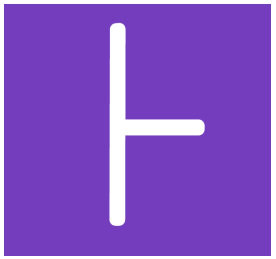

- C/C++, Java, Objective C

Smallfoot IR

Matching Semantic Effects in Intermediate Analysis Result

Match Fixing Properties

```
// [n] may be null
public static Node checkNotNull(Node n) {
  if (n == null) {
    throw new IllegalArgumentException("Bad Arg");
  }
  return n;
}
```

This procedure does good things

Match Fixing Properties

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// [n] may be null
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```

Desirable property:
Throw Exn when Node is null

Inferring a Procedure Specification

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2 Specifications inferred

PRE:
n != null ;
n → Node

POST:
n != null ;
n → Node;
return = n

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Desirable property:
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2 Specifications inferred

PRE:
n != null ;
n → Node

Object "Node" allocated on the heap

POST:
n != null ;
n → Node;
return = n

Match Fixing Properties

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Desirable property:
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2 Specifications inferred

PRE:
n != null ;
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POST:
n != null ;
n → Node;
return = n

PRE:
n → null
POST:
n = null;
return = java.lang.IllegalArgException

Match Fixing Properties

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Match!

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Compositionality Matters

Google error-prone

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Google error-prone

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```
public static void checkGuardedBy(boolean condition, String message) {
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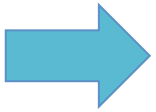
Google error-prone

Compositionality Matters



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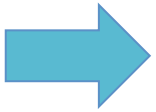
Google error-prone

Compositionality Matters



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```

Cannot be inferred here!

Google error-prone

Compositionality Matters

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public class GuardedByBinder {
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      Symbol.MethodSymbol method =
        context.resolver.resolveMethod(node, identifier.getName());
      PRE: {method == null}
      checkGuardedBy(method != null, identifier.toString());
      POST: {throw new IllegalArgumentException}
      return bindSelect(computeBase(context, method), method);
   }
}
```

Inferred here!

```
public static void checkGuardedBy(boolean condition, String message) {
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Google error-prone

Match Fixing Fragments

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```

Match ✓

Google error-prone

Apply Fixing Fragments

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      return bindSelect(computeBase(context, method), method);
 } case MEMBER_SELECT: {
       …
      Symbol.MethodSymbol method =
        context.resolver.resolveMethod(node, identifier.getName());
        // NULL DEREFERENCE ERROR
        return bindSelect(computeBase(context, method), method);
   }
}
```

Match ✓

Google error-prone

Apply Fixing Fragments

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Match ✓

Google error-prone

Validate Fixing Fragments

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```

Match ✓

Validate ✓

How We Formulate Repair

Repair in the Abstract

Repair in the Abstract

```
swHashMap *map = sw_malloc(sizeof(swHashMap));
…
if (error) {
   // map alloced but not freed
  return;
}
```

Repair in the Abstract

$\mathrm{C}_{\ell}, \mathrm{H}_{Bad} \rightsquigarrow$ fault

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IR Command C

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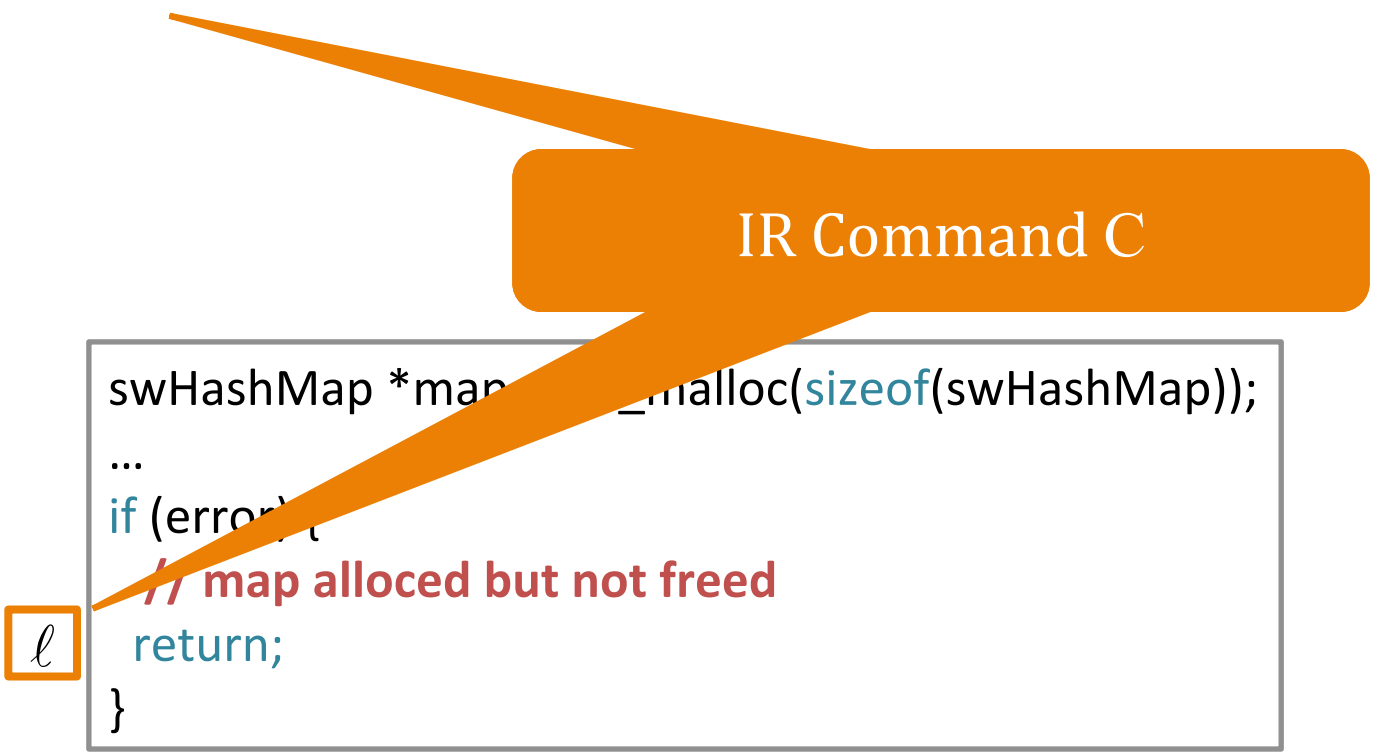

Repair in the Abstract

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Fault-inducing Heap state

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```

ℓ

Repair in the Abstract

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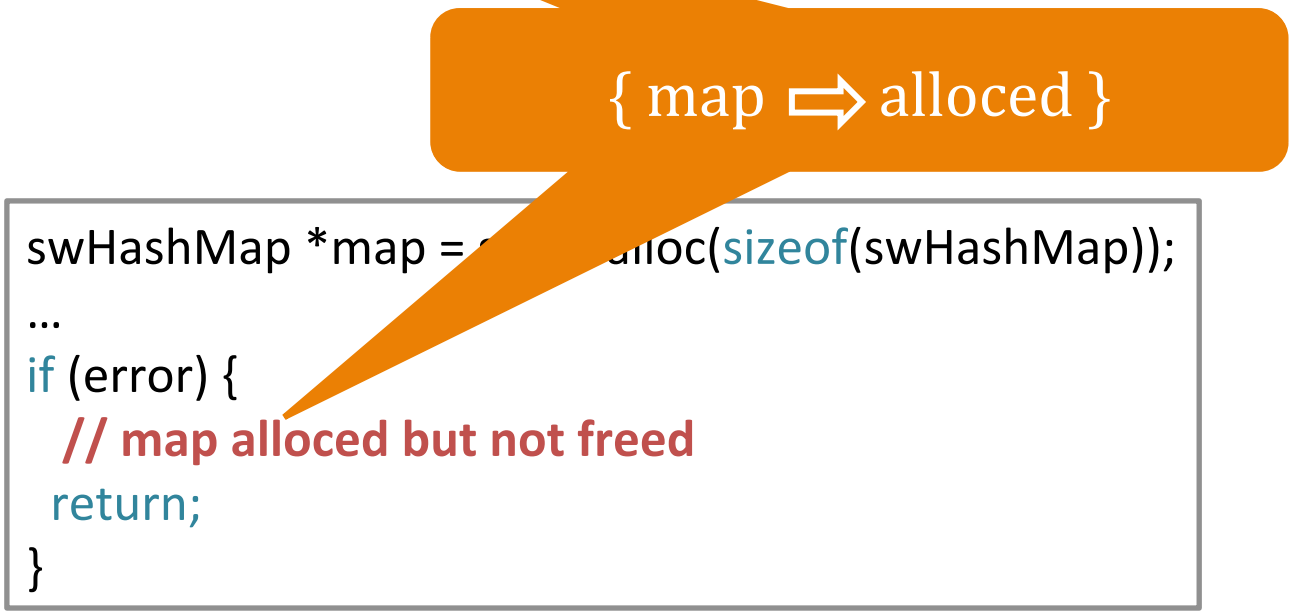

Repair in the Abstract

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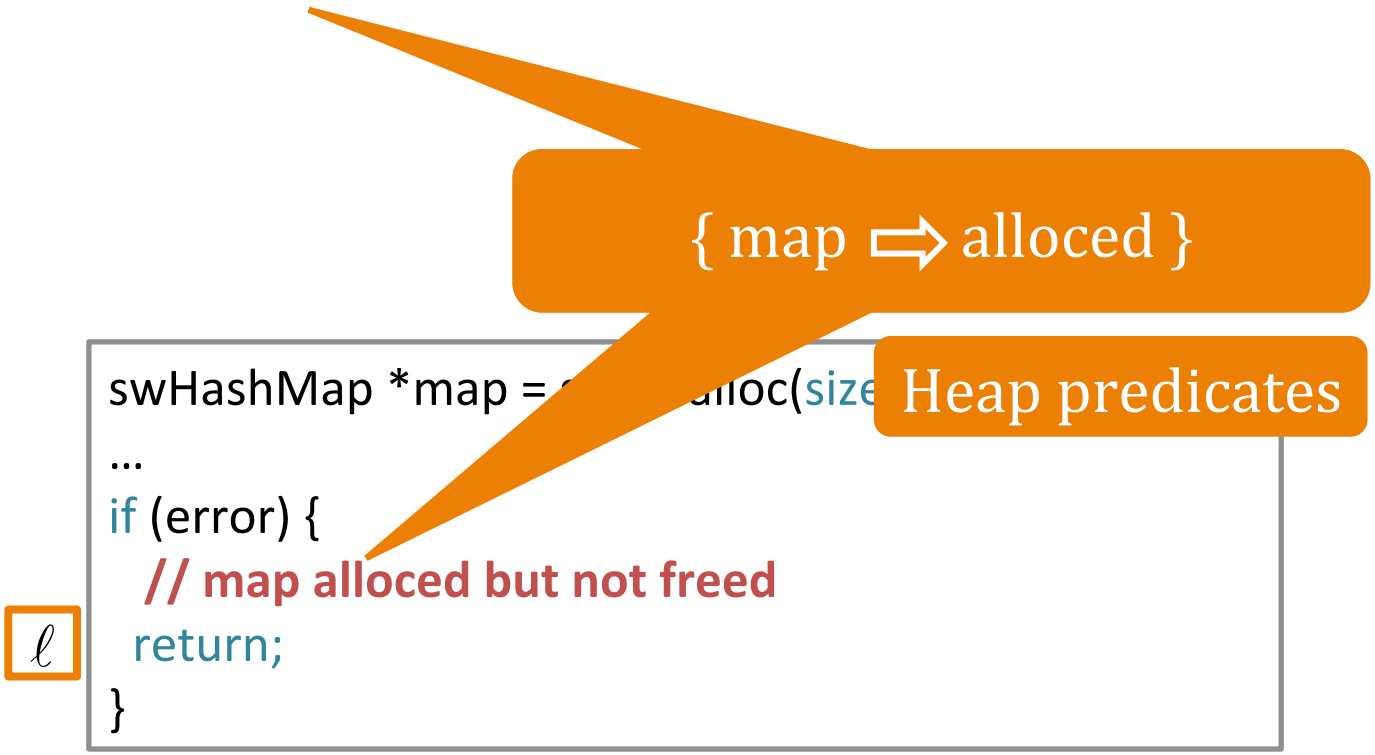

Repair in the Abstract

$\mathbf{C}_{\ell}, \mathbf{H}_{Bad} \rightsquigarrow$ fault

Interpretation step

```
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ℓ

Repair in the Abstract

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Bug report

```
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```

ℓ

Repair in the Abstract

$$\mathrm{C}_{\ell}, \mathrm{H}_{Bad} \rightsquigarrow \text{fault} \Rightarrow \mathrm{T}_{\ell'}, \mathrm{H} \overset{*}{\rightsquigarrow} \mathrm{C}_{\ell}, \mathrm{H}_{Good}$$

Fixing transformation T

ℓ

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Produce a "Good" heap state

```
swHashMap *map = sw_malloc(sizeof(swHashMap));
…
if (error) {
  // map alloced but not freed
ℓ  return;
}
```

Repair in the Abstract

$$\mathrm{C}_{\ell}, \mathrm{H}_{Bad} \rightsquigarrow \text{fault} \Rightarrow \mathrm{T}_{\ell'}, \mathrm{H} \overset{*}{\rightsquigarrow} \mathrm{C}_{\ell}, \mathrm{H}_{Good} \not\rightsquigarrow \text{fault}$$

Fault-avoiding interpretation

```
swHashMap *map = sw_malloc(sizeof(swHashMap));
…
if (error) {
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}
```

ℓ

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$$\mathrm{C}_{\ell}, \mathrm{H}_{Bad} \rightsquigarrow \text{fault} \Rightarrow \mathrm{T}_{\ell'}, \mathrm{H} \overset{*}{\rightsquigarrow} \mathrm{C}_{\ell}, \mathrm{H}_{Good} \not\rightsquigarrow \text{fault}$$

How to find T?

```
swHashMap *map = sw_malloc(sizeof(swHashMap));
…
if (error) {
  // map alloced but not freed
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}
```

ℓ

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Additive transformation

```
swHashMap *map = sw_malloc(sizeof(swHashMap));
...
if (error) {
+ sw_free(map);
  return;
}
```

ℓ

Repair in the Abstract

$$C_{\ell}, H_{Bad} \rightsquigarrow \text{fault} \Rightarrow T_{\ell'} H \overset{*}{\rightsquigarrow} C_{\ell}, H_{Good} \not\rightsquigarrow \text{fault}$$

At the reported error location

```
swHashMap *map = sw_malloc(sizeof(swHashMap));
…
if (error) {
  sw_free(map);
  return;
}
```

ℓ'

ℓ

Repair in the Abstract

$$\mathrm{C}_{\ell}, \mathrm{H}_{Bad} \rightsquigarrow \text{fault} \Rightarrow \mathrm{T}_{\ell'}, \mathrm{H} \overset{*}{\rightsquigarrow} \mathrm{C}_{\ell}, \mathrm{H}_{Good} \not\rightsquigarrow \text{fault}$$

{ map ⇨ freed }

```
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{ map ⇨ alloced }

{ map ⇨ freed }

```
swHashMap *map = sw_malloc(sizeof(swHashMap));
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if (error) {
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}
```

ℓ

Semantic Repair Search

$$C_{\ell}, H_{Bad} \rightsquigarrow \text{fault} \Rightarrow T_{\ell'}, H \overset{*}{\rightsquigarrow} C_{\ell}, H_{Good} \not\rightsquigarrow \text{fault}$$

{ map ⇨ alloced } ?C { map ⇨ freed }

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}
```

Semantic Repair Search

$$\mathrm{C}_{\ell}, \mathrm{H}_{Bad} \rightsquigarrow \text{fault} \Rightarrow \mathrm{T}_{\ell'}, \mathrm{H} \overset{*}{\rightsquigarrow} \mathrm{C}_{\ell}, \mathrm{H}_{Good} \not\rightsquigarrow \text{fault}$$

$\{ pvar \Rightarrow \text{alloced} \}$ $?\mathrm{C}$ $\{ pvar \Rightarrow \text{freed} \}$

sw_free(*pvar*);

ℓ

```
swHashMap *map = sw_malloc(sizeof(swHashMap));
...
if (error) {
  // map alloced but not freed
  return;
}
```

Semantic Repair Search

$$\mathrm{C}_{\ell}, \mathrm{H}_{Bad} \rightsquigarrow \text{fault} \Rightarrow \mathrm{T}_{\ell'}, \mathrm{H} \overset{*}{\rightsquigarrow} \mathrm{C}_{\ell}, \mathrm{H}_{Good} \not\rightsquigarrow \text{fault}$$

$\{ pvar \Rightarrow \text{alloced} \}$ $?\mathrm{C}$ $\{ pvar \Rightarrow \text{freed} \}$

sw_free(*pvar*);

ℓ

```
swHashMap *map = sw_malloc(sizeof(swHashMap));
...
if (error) {
  sw_free(map);
  return;
}
```

Semantic Repair Search

$$\mathrm{C}_{\ell}, \mathrm{H}_{Bad} \rightsquigarrow \text{fault} \Rightarrow \mathrm{T}_{\ell'}, \mathrm{H} \overset{*}{\rightsquigarrow} \mathrm{C}_{\ell}, \mathrm{H}_{Good} \not\rightsquigarrow \text{fault}$$

{ *pvar* ⇨ alloced } ?C { *pvar* ⇨ freed }

sw_free(*pvar*);

```
swHashMap *map = sw_malloc(sizeof(swHashMap));
…
if (error) {
  sw_free(map);
  return;
}
```

ℓ

```
#define sw_free(ptr)
if (ptr) {
  free(ptr);
  ptr = NULL;
  swWarn("free");
}
```

Semantic Repair Search

$$C_{\ell}, H_{Bad} \rightsquigarrow \text{fault} \Rightarrow T_{\ell'}, H^{*}_{\ldots} \not\rightsquigarrow \text{fault}$$

{ *pvar* ⇨ alloced } ?C { *pvar* ⇨ freed }

Type "swHashMap *"

sw_free(***pvar***);

```
swHashMap *map = sw_malloc(sizeof(swHashMap));
…
if (error) {
  sw_free(map);
  return;
}
```

ℓ

```
#define sw_free(ptr)
if (ptr) {
  free(ptr);
  ptr = NULL;
  swWarn("free");
}
```

Type "void *"

Semantic Repair Search

$$\mathrm{C}_{\ell}, \mathrm{H}_{Bad} \rightsquigarrow \text{fault} \;\Rightarrow\; \mathrm{T}_{\ell'}, \mathrm{H} \overset{*}{\rightsquigarrow} \mathrm{C}_{\ell}, \mathrm{H}_{Good} \not\rightsquigarrow \text{fault}$$

$$\{\, pvar \Rightarrow \text{alloced} \,\} \;\; ?\mathrm{C} \;\; \{\, pvar \Rightarrow \text{freed} \,\}$$

Semantic Repair Search

$$\mathrm{C}_{\ell}, \mathrm{H}_{Bad} \rightsquigarrow \text{fault} \Rightarrow \mathrm{T}_{\ell'}, \mathrm{H} \overset{*}{\rightsquigarrow} \mathrm{C}_{\ell}, \mathrm{H}_{Good} \not\rightsquigarrow \text{fault}$$

$$\{\, pvar \Rightarrow \text{open} \,\} \quad ?\mathrm{C} \quad \{\, pvar \Rightarrow \text{close} \,\}$$

Semantic Repair Search

$$\mathrm{C}_{\ell}, \mathrm{H}_{Bad} \rightsquigarrow \text{fault} \Rightarrow \mathrm{T}_{\ell'}, \mathrm{H} \overset{*}{\rightsquigarrow} \mathrm{C}_{\ell}, \mathrm{H}_{Good} \not\rightsquigarrow \text{fault}$$

$$\{ \mathrm{F} \} \quad ?\mathrm{C} \quad \{ \mathrm{F}' \}$$

Local Reasoning & Separation Logic

$$\{ F \} \quad ?C \quad \{ F' \}$$

Local Reasoning & Separation Logic

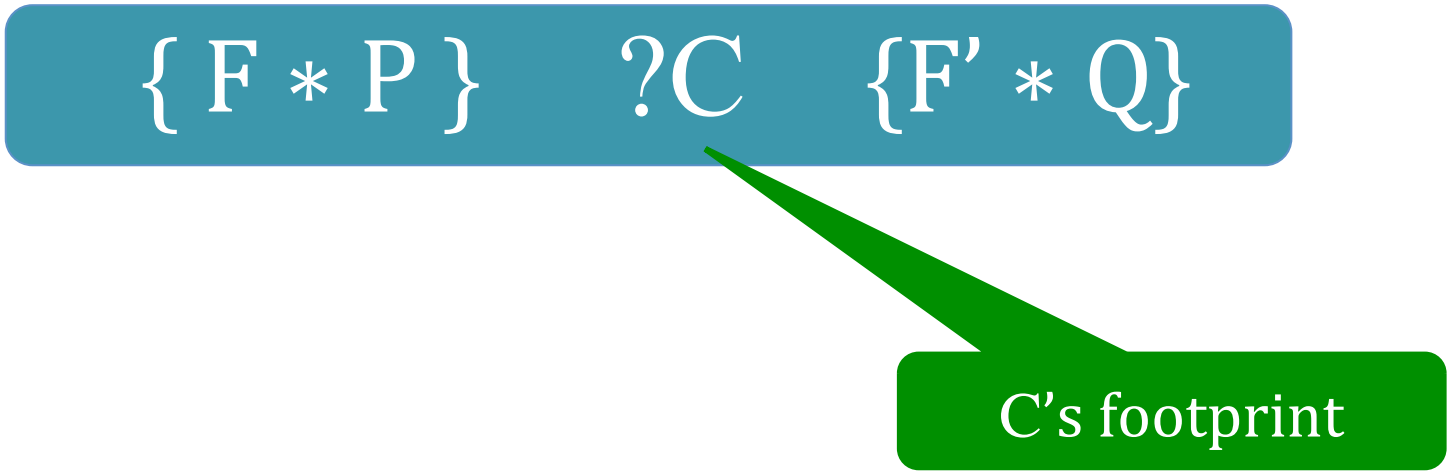
$$\{ F * P \} \quad ?C \quad \{F' * Q\}$$

Local Reasoning & Separation Logic

$$\{ F * P \} \quad ?C \quad \{F' * Q\}$$

C can affect other things on the heap

Local Reasoning & Separation Logic



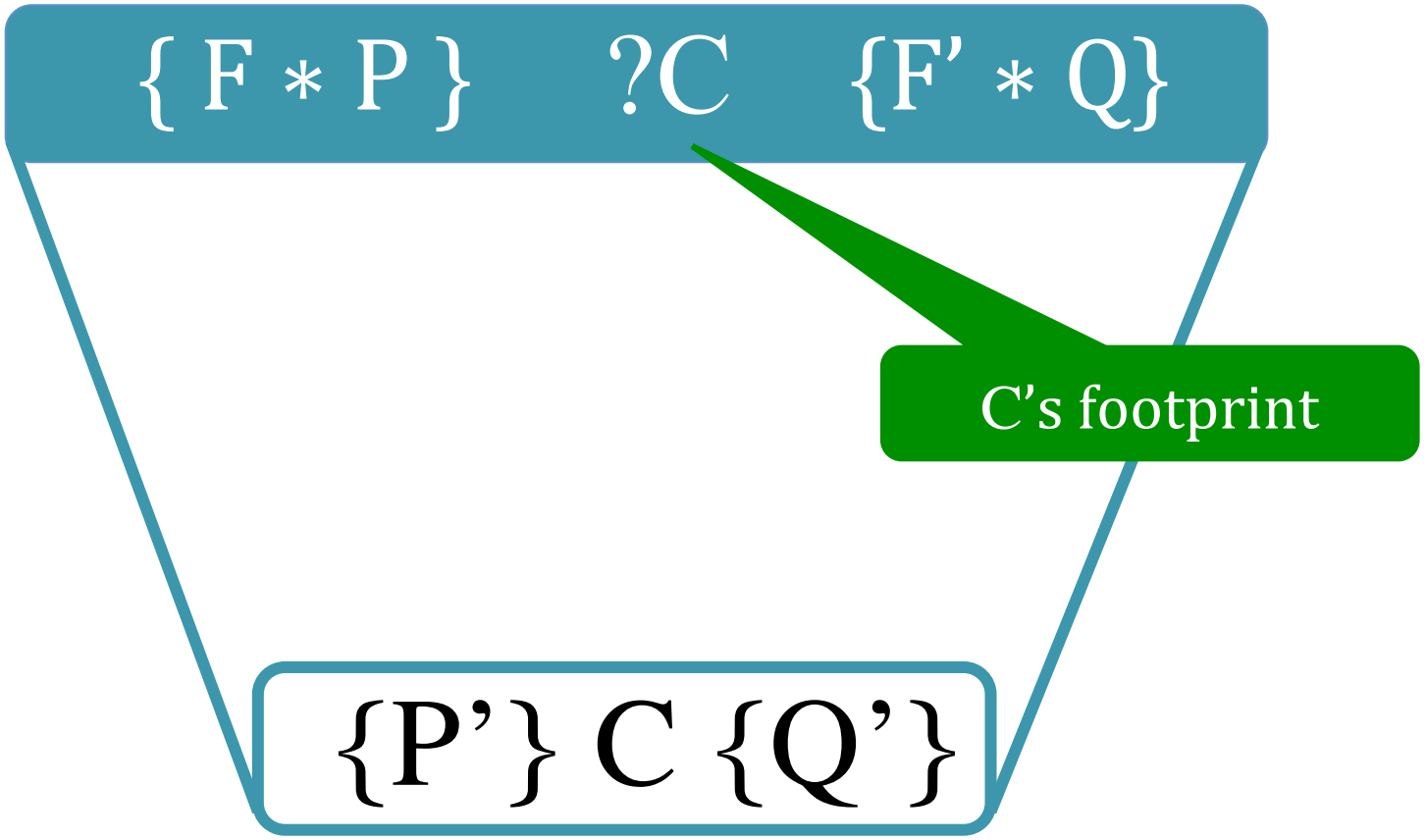
Local Reasoning & Separation Logic

$$\{ F * P \} \quad ?C \quad \{F' * Q\}$$

C's footprint

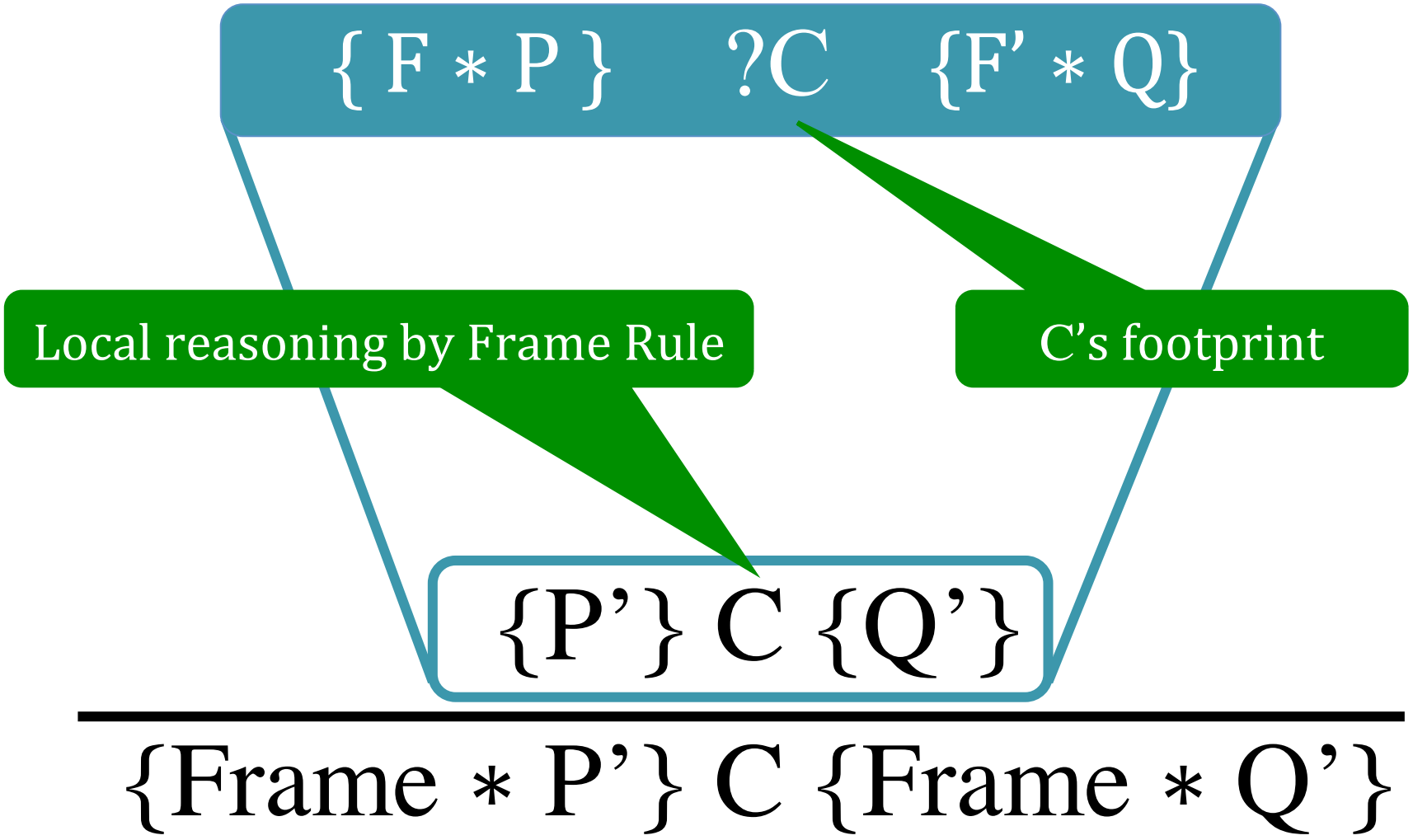
$$\frac{\{P'\}\ C\ \{Q'\}}{\{Frame * P'\}\ C\ \{Frame * Q'\}}$$

Local Reasoning & Separation Logic



$$\frac{\{P'\}\ C\ \{Q'\}}{\{Frame * P'\}\ C\ \{Frame * Q'\}}$$

Local Reasoning & Separation Logic



Results Summary

Results Summary

- 8 C projects and 3 Java projects

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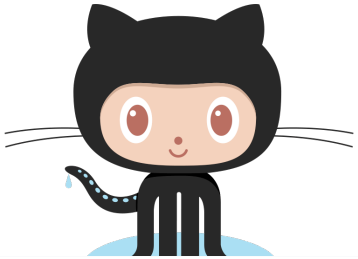
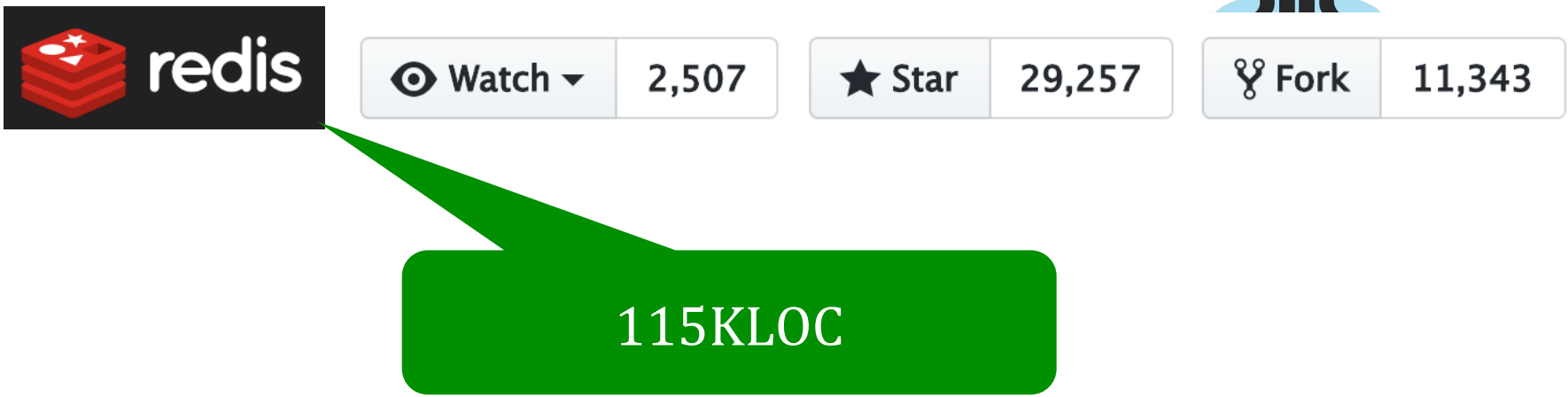
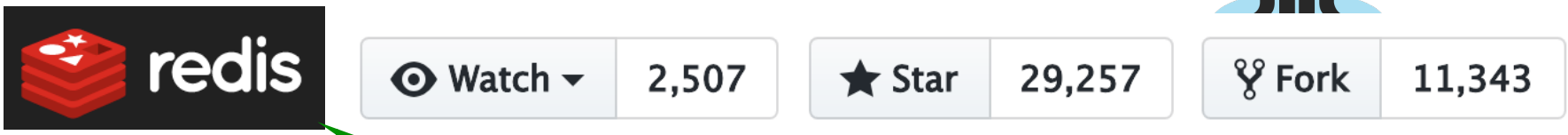
- 8 C projects and 3 Java projects





Results Summary

- 8 C projects and 3 Java projects

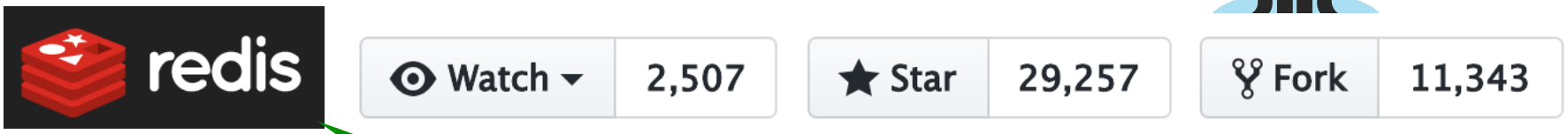


115KLOC

79 seconds

Results Summary

- 8 C projects and 3 Java projects



115KLOC

79 seconds

6 resource leak fixes

Results Summary

- 8 C projects and 3 Java projects

redis

Watch 2,507 Star 29,257 Fork 11,343

SWOLE

Watch 836 Star 8,973 Fork 2,137

Results Summary

- 8 C projects and 3 Java projects

redis

Watch 2,507 Star 29,257 Fork 11,343

SWOLE

Watch 836 Star 8,973 Fork 2,137

APKTOOL

Watch 501 Star 6,288 Fork 1,790

Results Summary

- 8 C projects and 3 Java projects

redis — Watch 2,507 | Star 29,257 | Fork 11,343

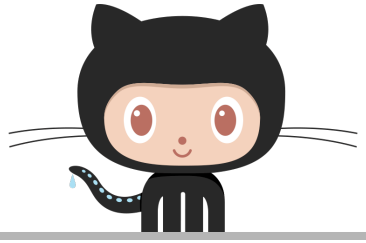
SWOLE — Watch 836 | Star 8,973 | Fork 2,137

APKTOOL — Watch 501 | Star 6,288 | Fork 1,790

LXC — Watch 201 | Star 2,162 | Fork 700

Results Summary

- 8 C projects and 3 Java projects



Fix memory leak in _attach_new_segment #528

Merged **rhc54** merged 1 commit into `pmix:master` from `footpatch:patch-1`

Fix file descriptor leak #45

Merged **KoffeinFlummi** merged 1 commit into `KoffeinFlummi:master` from `footpatch:patch-1`

Close input stream in SmaliMod.java #1599

Merged **iBotPeaches** merged 1 commit into `iBotPeaches:master` from `footpatch:patch-1`

Results Summary

Project	Lang	KLOC	Time (s)	Bug	Fixes	False Pos
Swoole	C	44	20	Res. Leak	1	0
				Mem. Leak	6	3
lxc	C	63	51	Res. Leak	1	0
				Mem. Leak	0	1
Apktool	Java	15	584	Res. Leak	1	0
dablooms	C	1	9	Res. Leak	7	0
php-cp	C	9	20	Res. Leak	1	0
armake	C	16	10	Res. Leak	4	0
sysstat	C	24	28	Res. Leak	1	0
redis	C	115	79	Res. Leak	6	0
rappel	C	2	7	Mem. Leak	1	0
error-prone	Java	149	262	Null Deref	2	0
jfreechart	Java	282	1,268	Null Deref	22	0

Results Summary

Project	Lang	KLOC	Time (s)	Bug	Fixes	False Pos
Swoole	C	44	20	Res. Leak	1	0
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php-cp	C	9	20	Res. Leak	1	0
armake	C	16	10	Res. Leak	4	0
sysstat	C	24	28	Res. Leak	1	0
redis	C	115	79	Res. Leak	6	0
rappel	C	2	7	Mem. Leak	1	0
error-prone	Java	149	262	Null Deref	2	0
jfreechart	Java	282	1,268	Null Deref	22	0

4 false positives

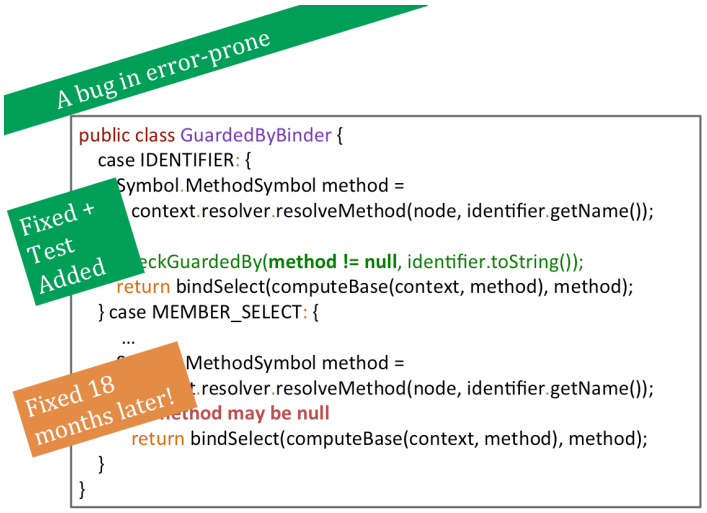
Results Summary

Project	Lang	KLOC	Time (s)	Bug	Fixes	False Pos
Swoole	C	44	20	Res. Leak	1	0
				Mem. Leak	6	3
lxc		63	51	Res. Leak	1	0
				eak	0	1
Apktool				ak	1	0
dablooms				ak	7	0
php-cp				ak	1	0
armake				ak	4	0
sysstat				ak	1	0
redis				eak	6	0
rappel	C	2	7	Mem. Leak	1	0
error-prone	Java	149	262	Null Deref	2	0
jfreechart	Java	282	1,268	Null Deref	22	0

55 fixes
- 24 resource leaks
- 7 memory leaks
- 24 null dereferences

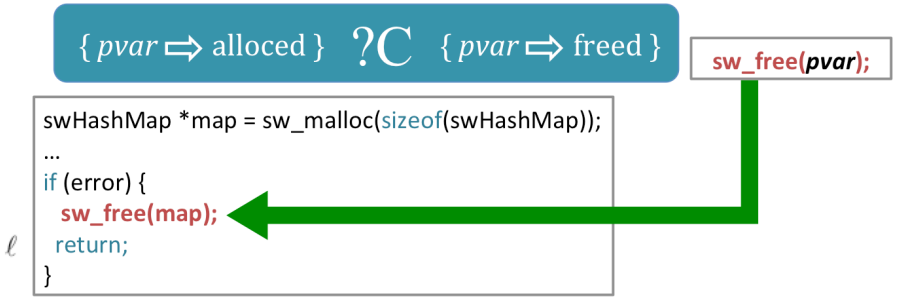
Summary

Static Analysis for APR

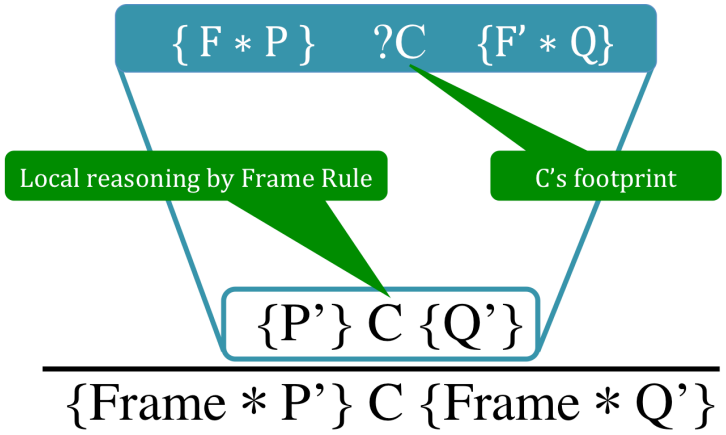


Repair in the Abstract

$$C_{\ell}, H_{Bad} \rightsquigarrow \text{fault} \Rightarrow T_{\ell'}, H \overset{*}{\rightsquigarrow} C_{\ell}, H_{Good} \not\rightsquigarrow \text{fault}$$

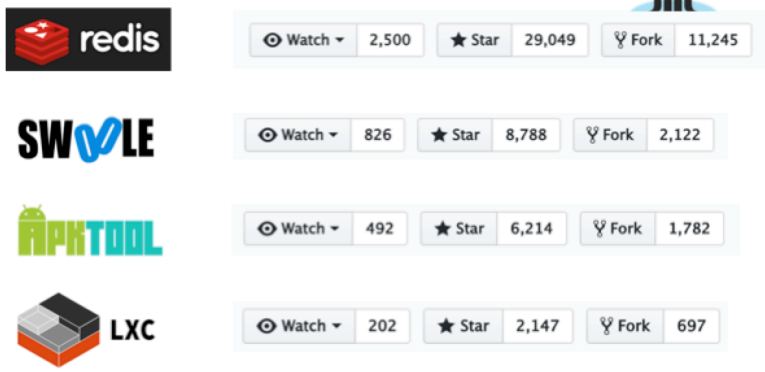


Local Reasoning & Separation Logic



Fix Real Bugs

- 8 C projects and 3 Java projects



https://github.com/squaresLab/footpatch