Learning to Find Bugs in Programs and their Documentation

Andrew Habib

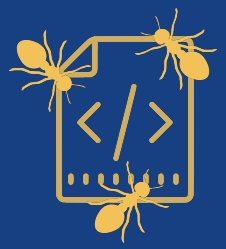
TU Darmstadt

software-lab.org

PhD Defense – December 14th, 2020

Software Bugs

- **Bugs are everywhere**
  - 15-50 buggy LoC per 1,000 LoC[1]



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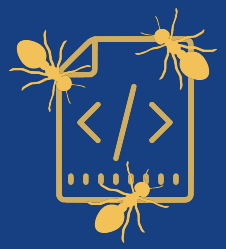

- **Software failures in 2018**[2]
  - Affect many people: ½ the world population
  - Costly: USD 1.7 trillions in assets

1 Steve McConnell. Code Complete: A Practical Handbook of Software Construction
2 The Software Fail Watch, 5th edition

Detecting Software Bugs

E.g.: Static analysis, dynamic analysis, model checking

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  E.g.: Source code, runtime information, predefined specifications

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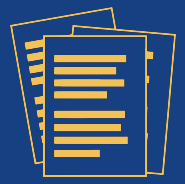
- Focus on traditional artifacts only
  E.g.: Source code, runtime information, predefined specifications
- Ignore rich source of information: Documentation

Software Documentation

API documentation



- Developers intentions & assumptions
- Easy to understand by humans
- Abundance of information

Software Documentation

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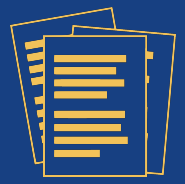

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Can we use software documentation to find bugs?

Using Documentation to Find Bugs

API Documentation Challenges

Using Documentation to Find Bugs

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- Fuzzy natural language

Using Documentation to Find Bugs

API Documentation Challenges

- **Fuzzy natural language**
- **Code evolves rapidly, documentation:**
  - Missing information
  - Stale or outdated
  - Inconsistent

Using Documentation to Find Bugs

API Documentation Challenges

- **Fuzzy natural language**
- **Code evolves rapidly, documentation:**
  - Missing information
  - Stale or outdated
  - Inconsistent
- **Unclear documentation best practices**

API Documentation Issues Ex. (1)

E.g.: JDK format classes (`DateFormat`, `MessageFormat`, `NumberFormat`)

Bug report:[1]

> *"[...] Not being thread-safe is a significant limitation on a class (sic), with potentially dire results, and not documenting the classes as such is dangerous."*

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Problem: Missing thread safety documentation

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Problem: **Missing thread safety documentation**
Solution: **Document classes as <u>not</u> thread-safe**

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API Documentation Issues Ex. (2)

E.g.: commons lang `StringUtils.unwrap`

Documentation:

```
public static String unwrap(String str, String wrapToken)
Unwraps a given string from another string.  ...
Parameters:
str - the String to be unwrapped, can be null
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unwrapped String or the original string if it is
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Invocation:[1]

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Problem: Unexpected (undocumented) exception

Solution: Fix the corner case in the implementation

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PhD Thesis Statement

Automatically learning from programs and their documentation provides an effective means to prevent and detect software bugs.

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Documentation

Source code

Runtime behavior

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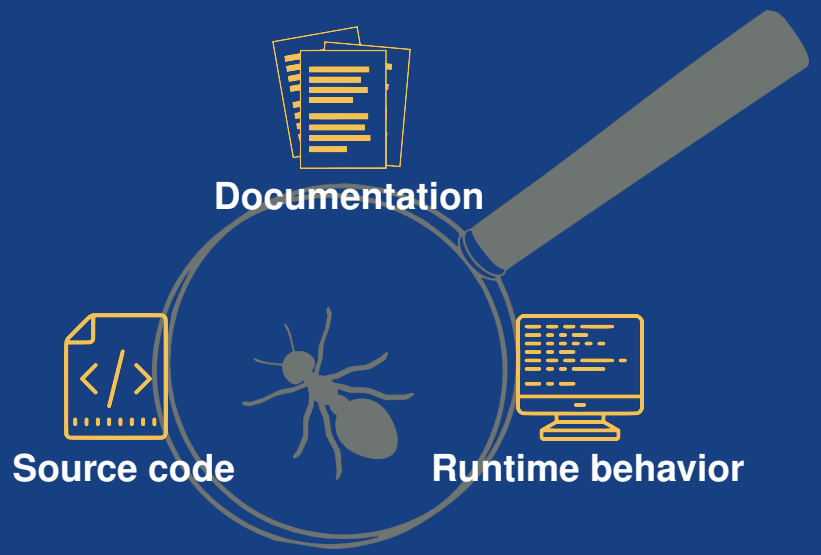


PhD Thesis

Learning from Programs and their Documentation

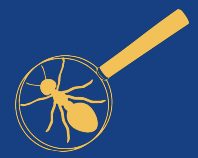
Source code

Documentation

PhD Thesis

Learning from Programs and their Documentation

Chapter 2
y of state-of-the-art tools



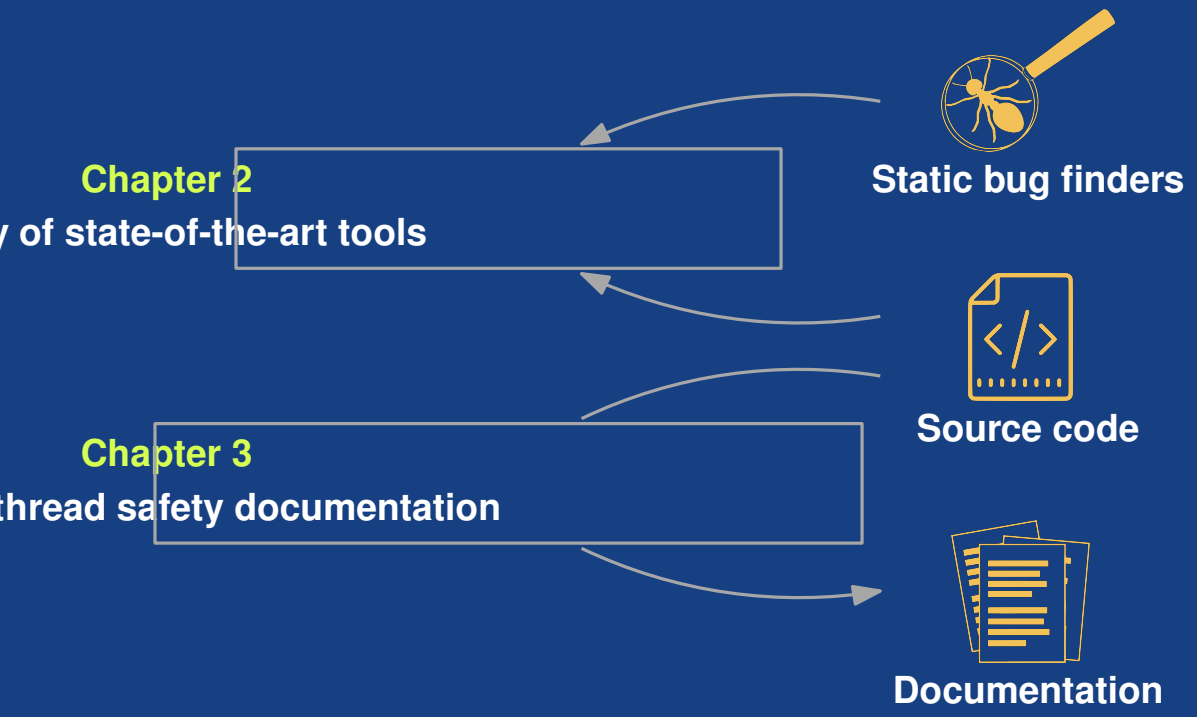
Static bug finders

Source code

Documentation

PhD Thesis

Learning from Programs and their Documentation



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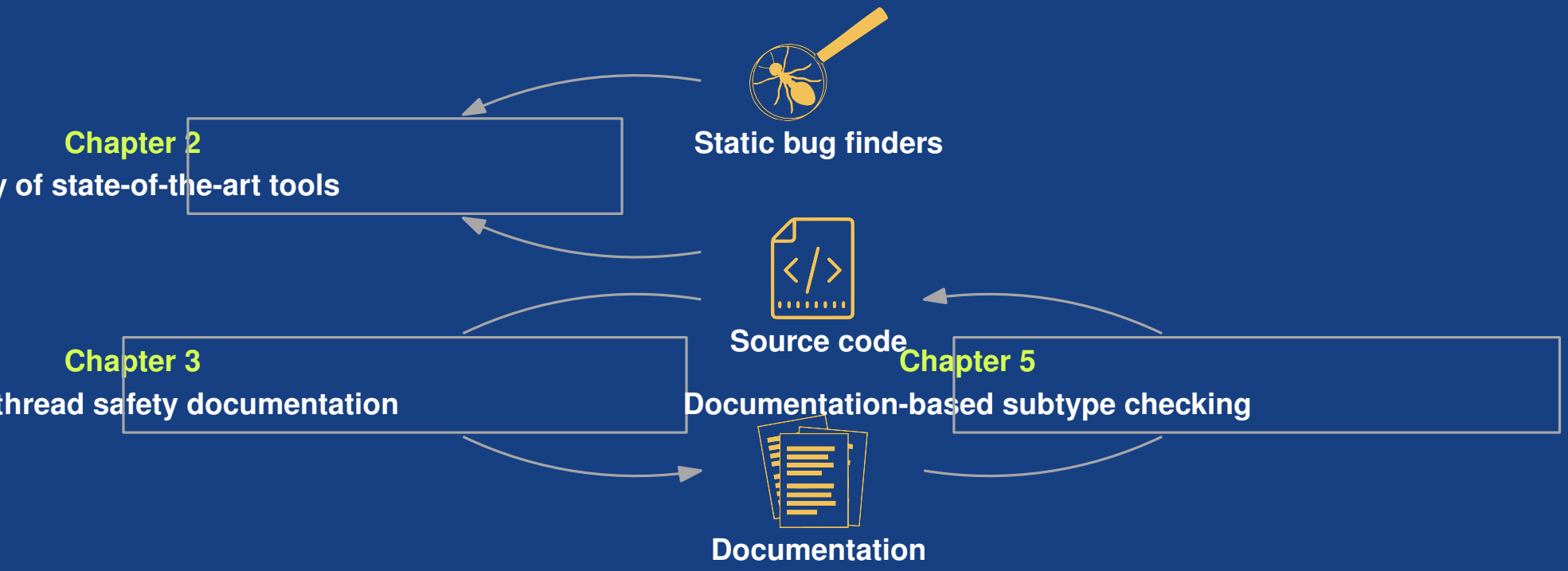

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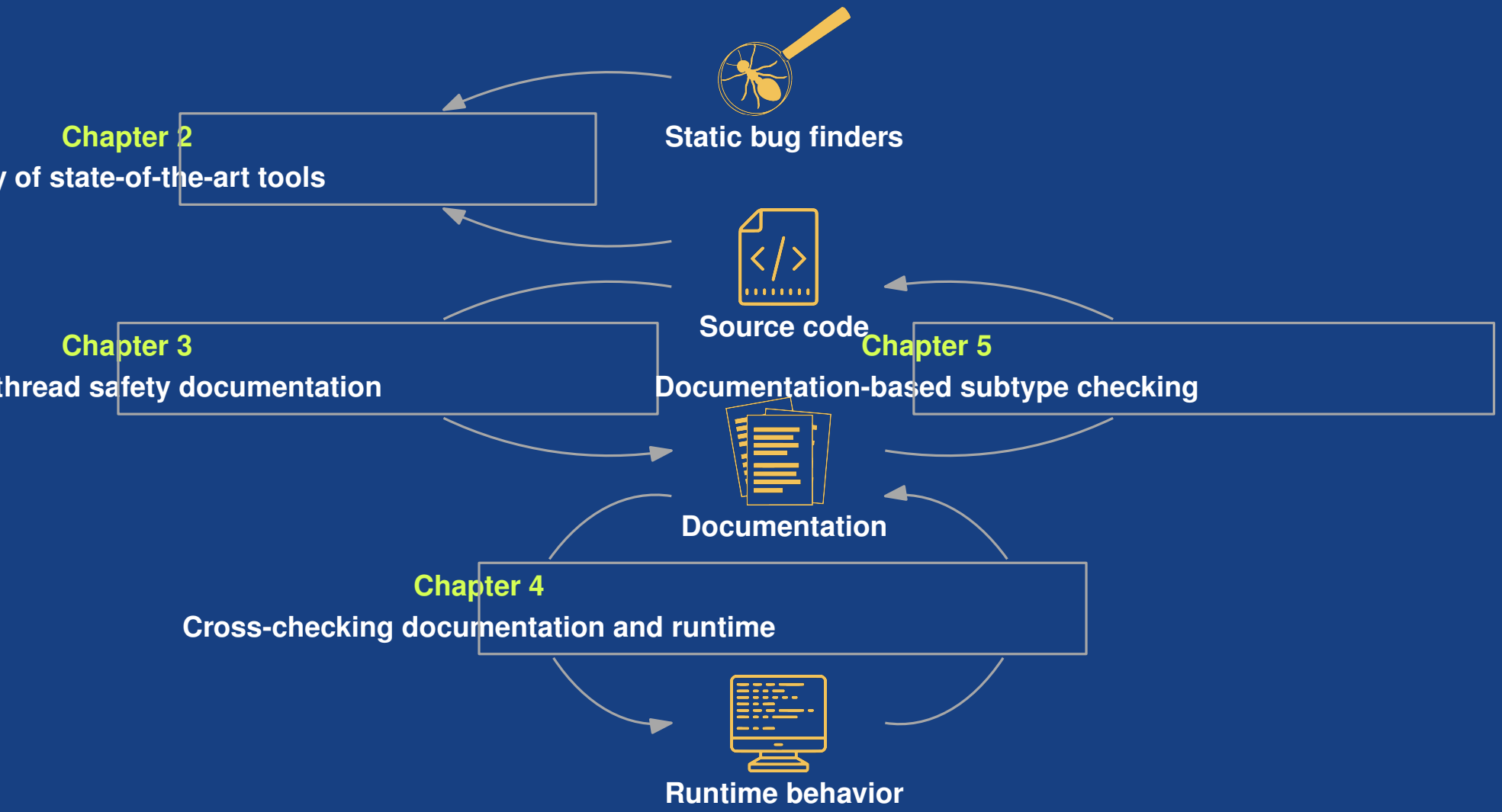

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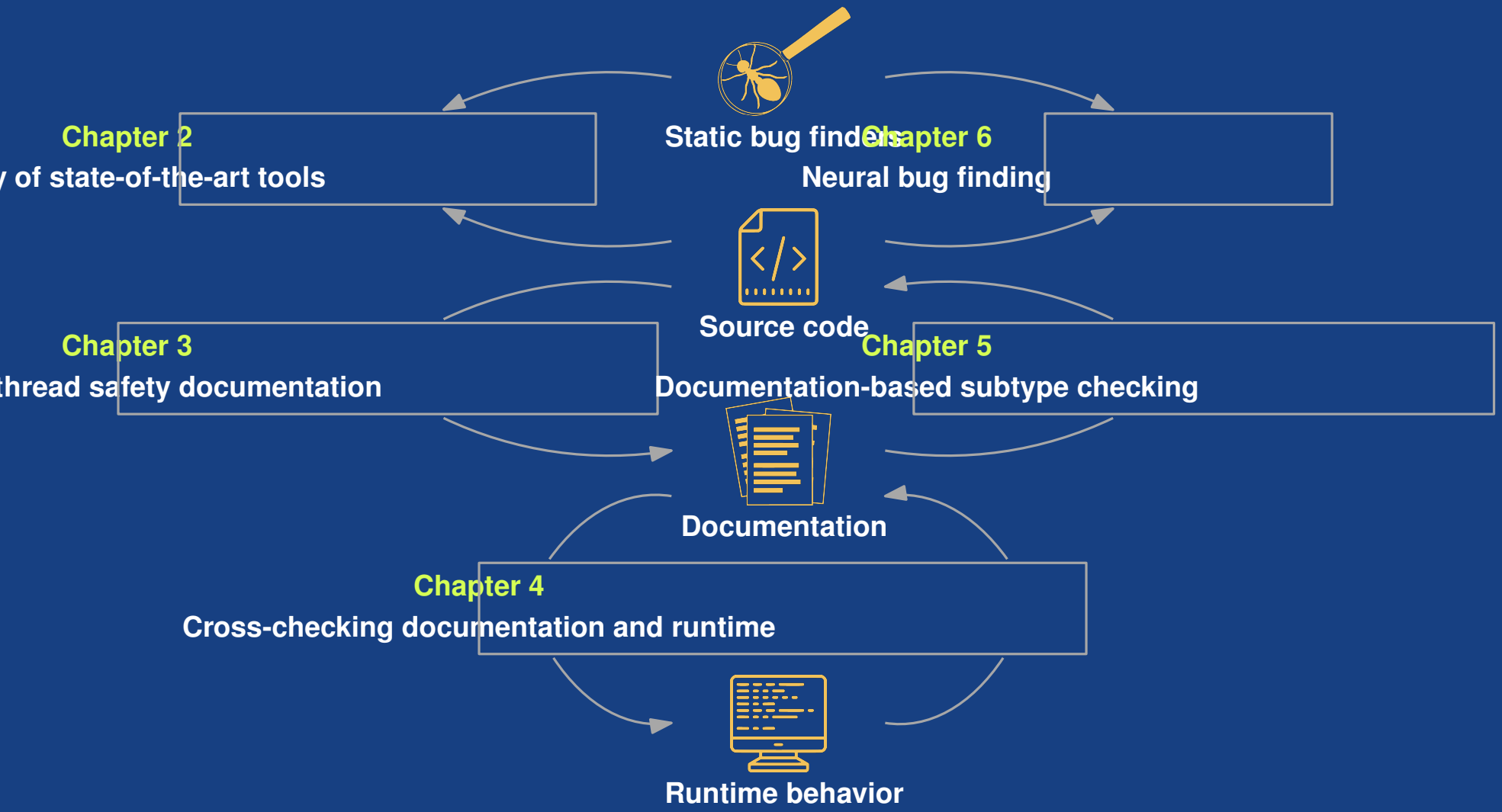

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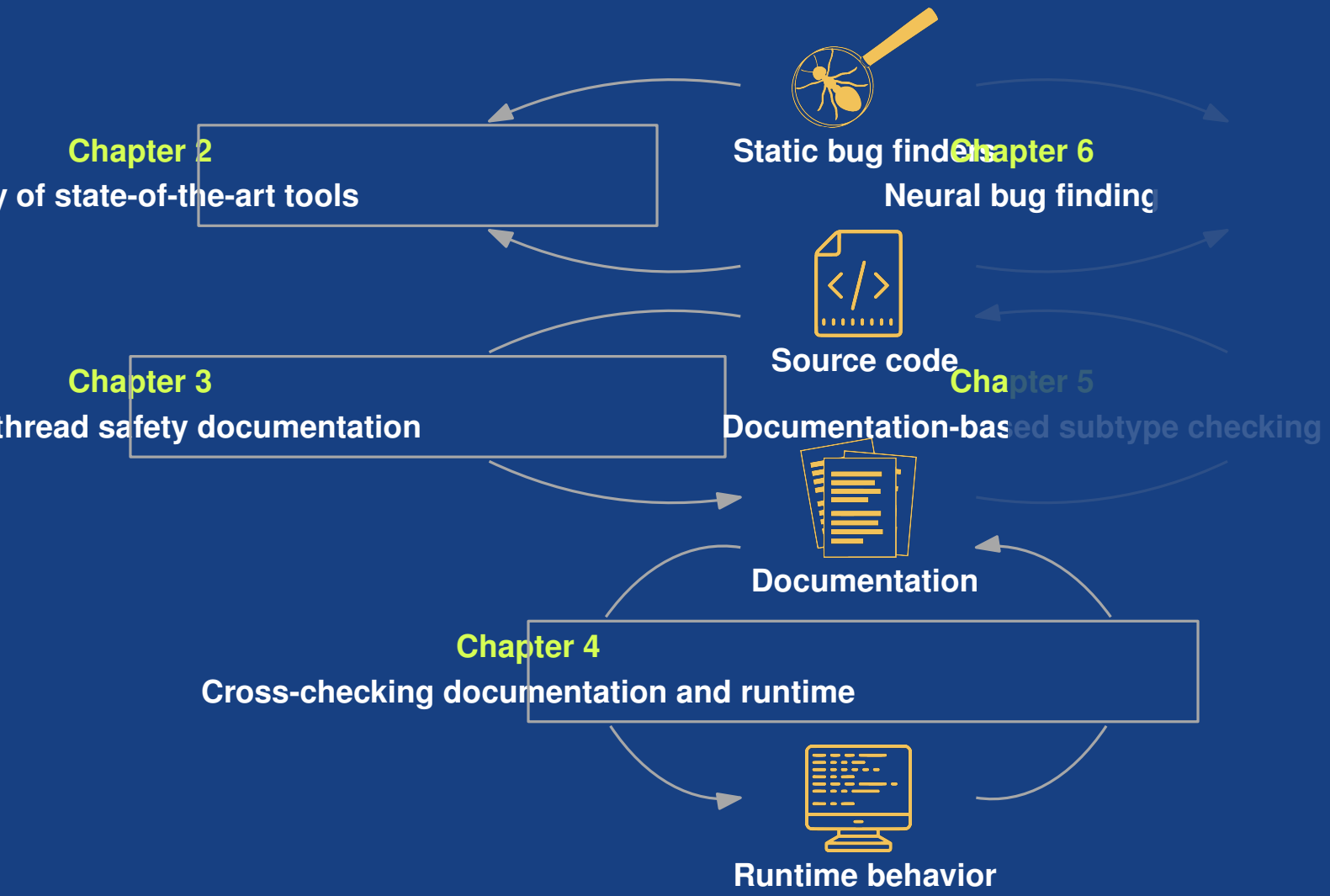

What is the state of static bug finding?

How Many of All Bugs Do We Find? A Study of Static Bug Detectors.
Andrew Habib and Michael Pradel. IEEE/ACM International Conference on Automated Software Engineering (ASE) 2018
(Chapter 2)

Static Bug Detectors

Google
Error Prone

facebook
Infer

SpotBugs

Static Bug Detectors

Google
Error Prone

facebook
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SpotBugs

How Many Bugs Do They Find?

Static Bug Detectors

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~~How Many Bugs Do They Find?~~

Given a representative set of real-world bugs, how many of them do static bug detectors find?

Real-World Bugs: Defects4J

594 bugs from 15 popular Java projects

- Extended version of Defects4J data set[1]

1 Just et al., Defects4J: A Database of Existing Faults to Enable Controlled Testing Studies for Java Programs. ISSTA'14

Real-World Bugs: Defects4J

594 bugs from 15 popular Java projects

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Why this set?

- Gathered independently
- Used in other bug-related studies[2]
- Contains real fixes by developers

1 Just et al., Defects4J: A Database of Existing Faults to Enable Controlled Testing Studies for Java Programs. ISSTA'14
2 Just et al., 2014 (mutation testing); Shamshiri et al., 2015 (test generation); Pearson et al., 2017 (fault localization); Martinez et al., 2017 (program repair)

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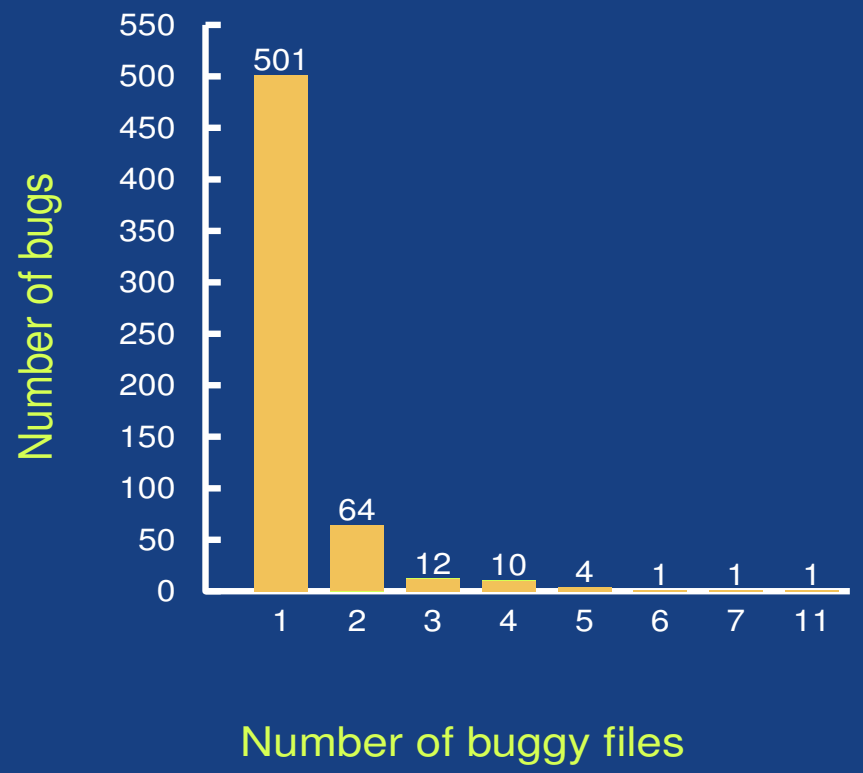

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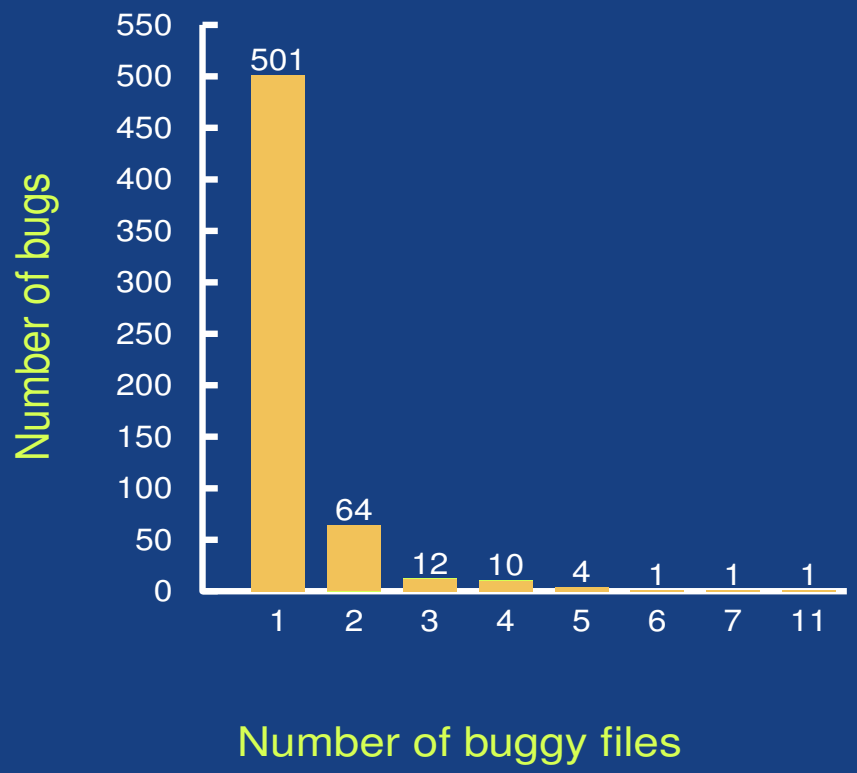

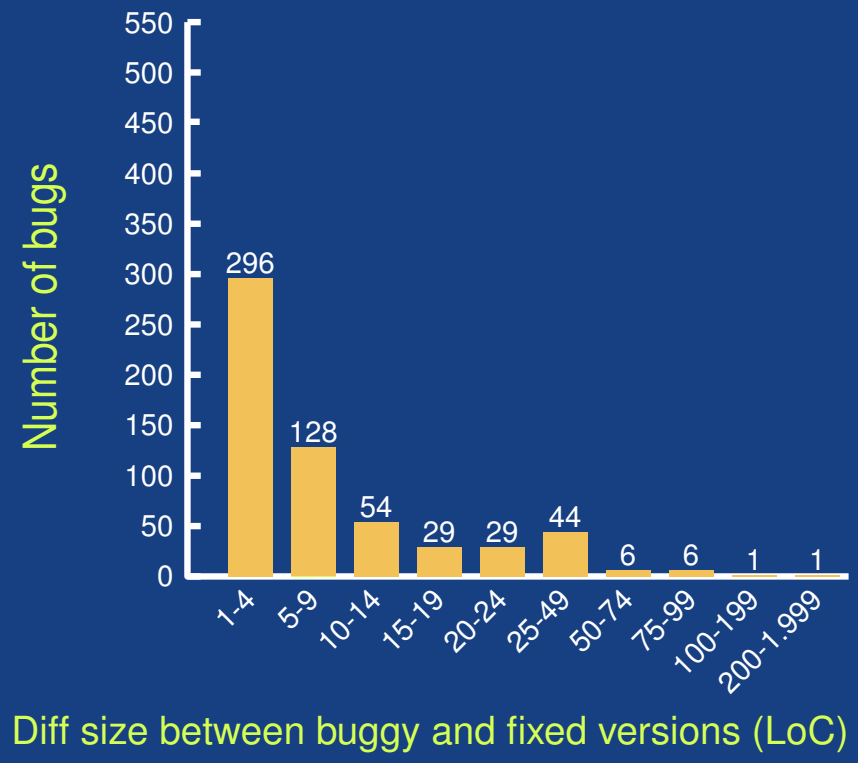

How to Determine Detected Bugs?

Bugs + fixes

Bug detectors

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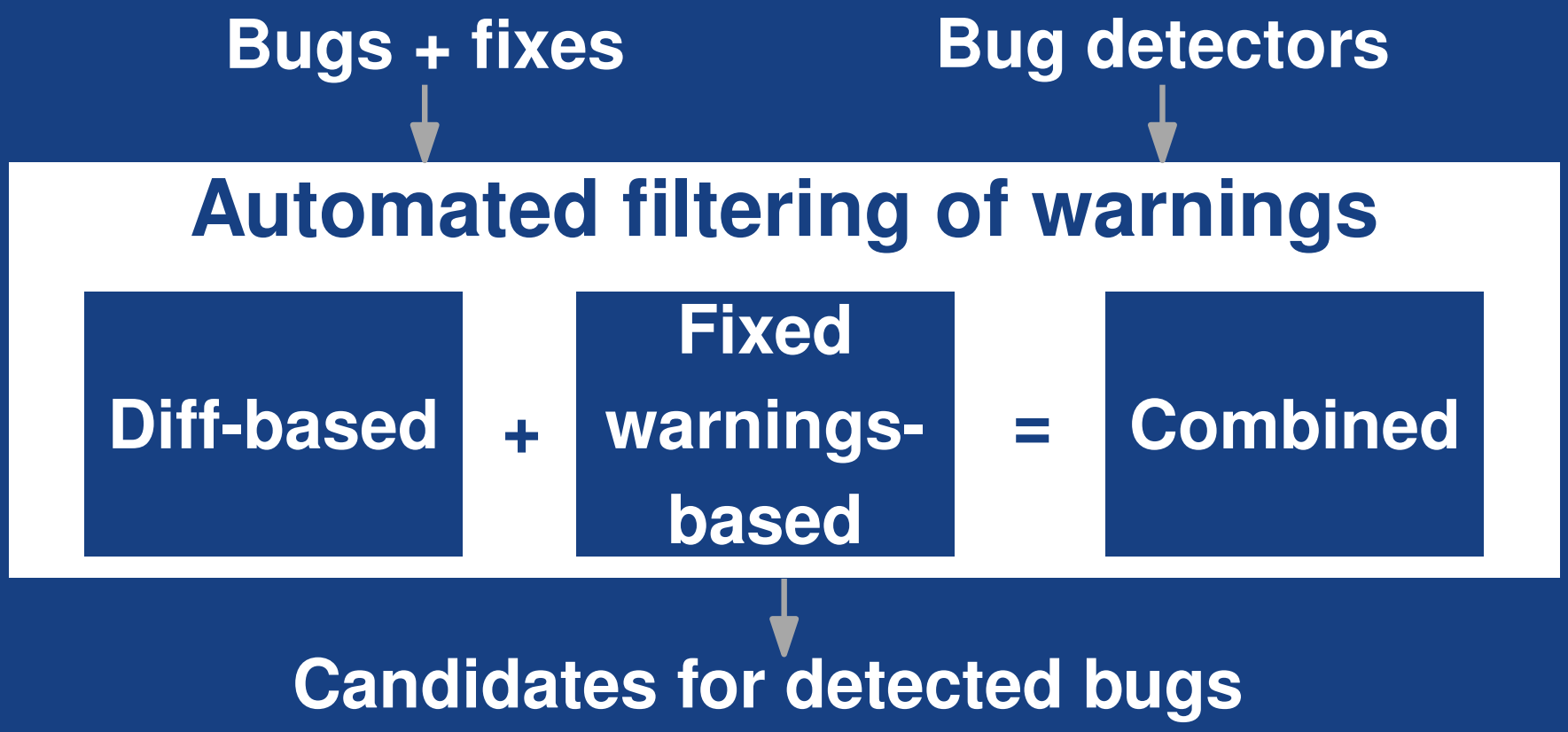
Automated filtering of warnings

Diff-based	+	Fixed warnings-based	=	Combined

How to Determine Detected Bugs?



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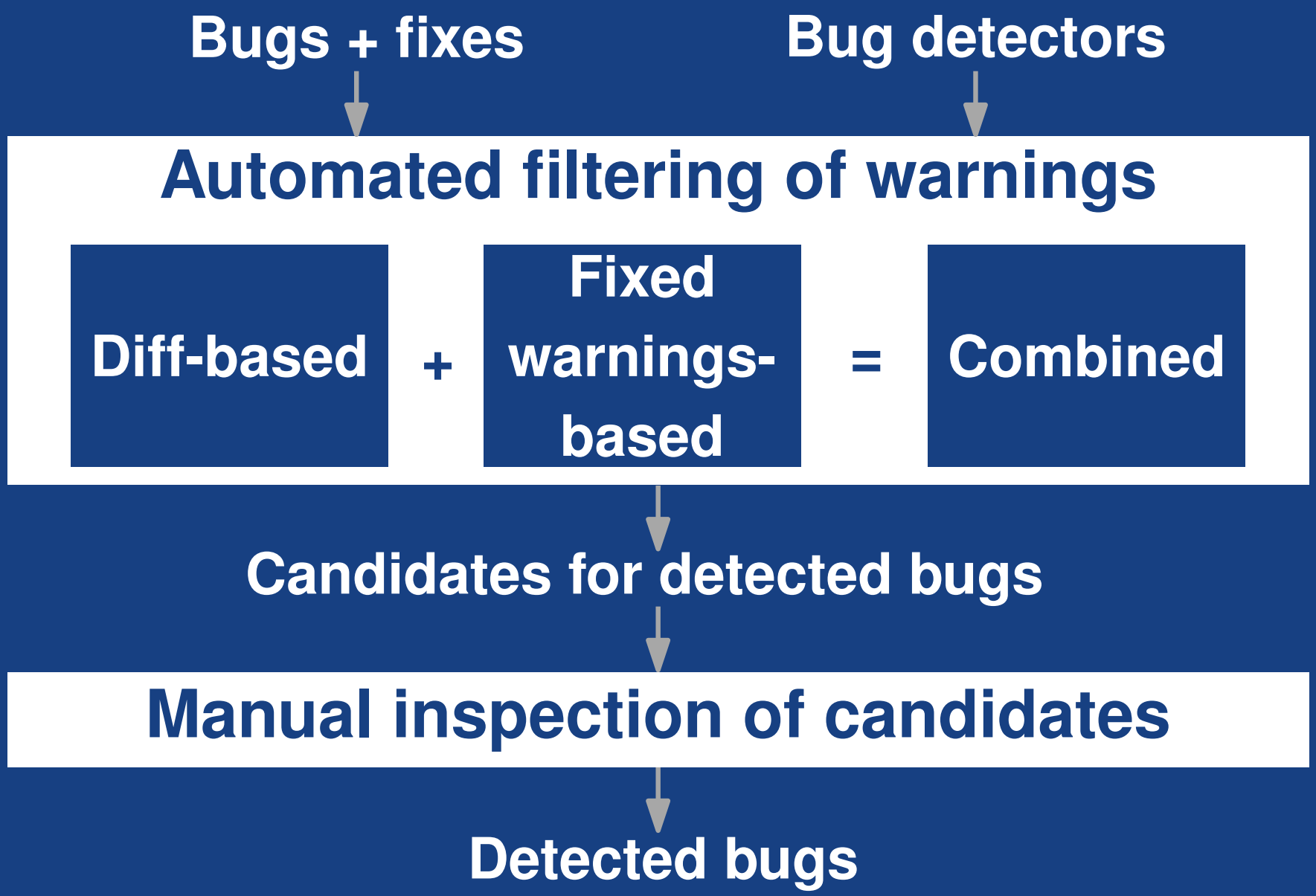

Warnings to Inspect

	All warnings			
	Per bug			
Tool	Min	Max	Avg	Total
Error Prone	0	148	7.58	4,402
Infer	0	36	0.33	198
SpotBugs	0	47	1.1	647
Total				**5,247**

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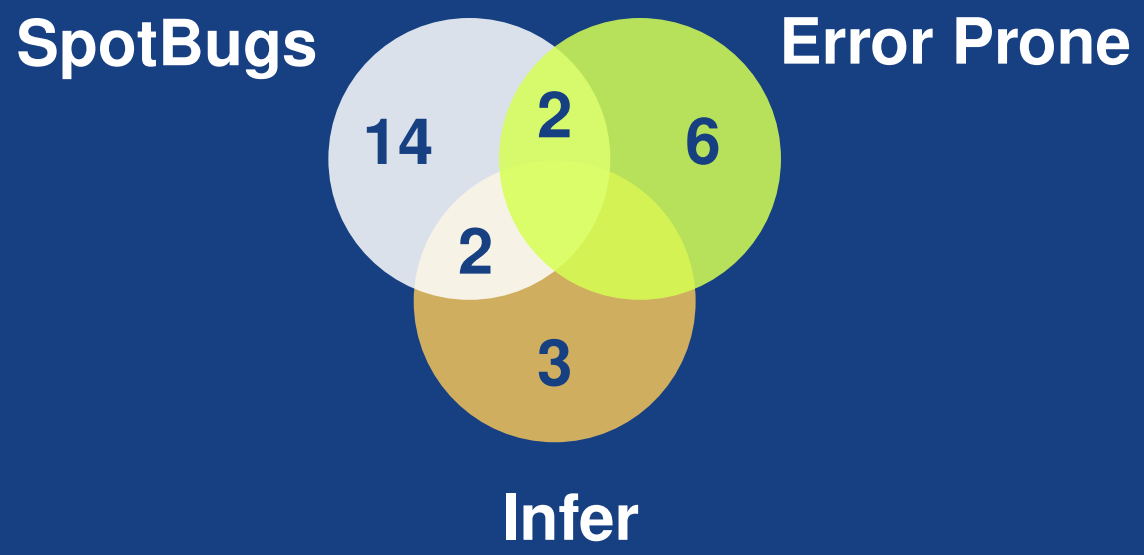
97% of all warnings are removed by the automated filtering step

Our Findings

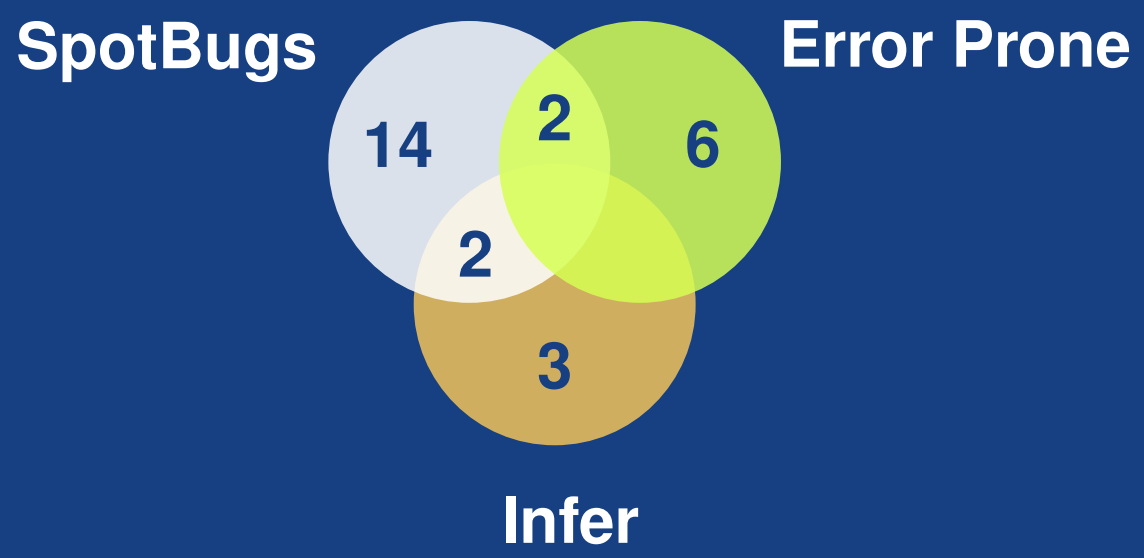
Our Findings



The three tools together:

Detect 27 out of 594 bugs

Our Findings



The three tools together:

Detect 27 out of 594 bugs

95.5% of the bugs are missed!

Our Findings (2)

Sample of 20 missed bugs:

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- **14/20 require domain-specific knowledge, e.g.:**
  - Joda-Time leap year
  - Closure compiler specific function declaration

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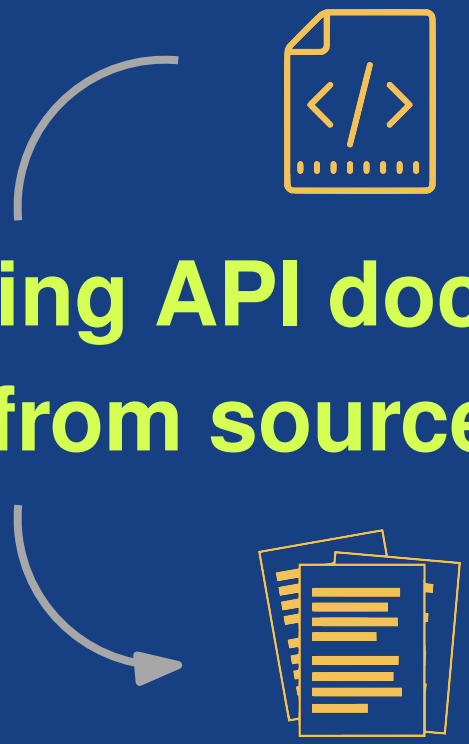
  - index out-of-bounds checker, but only for arrays, not ArrayLists
- **Huge room for improvement**

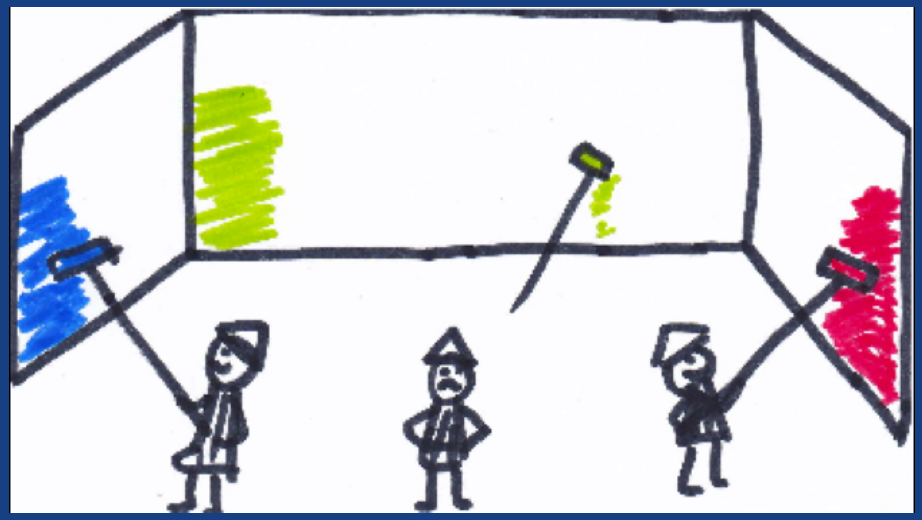


Learning API documentation from source code

Is This Class Thread-Safe? Inferring Documentation using Graph-Based Learning. Andrew Habib and Michael Pradel. IEEE/ACM International Conference on Automated Software Engineering (ASE) 2018

(Chapter 3)

Thread-Safe Classes



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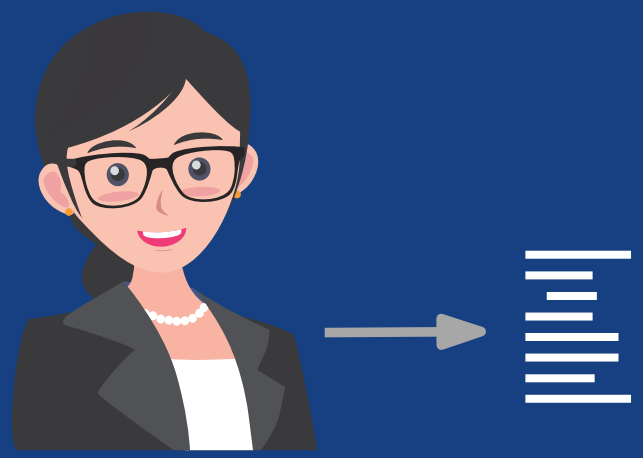

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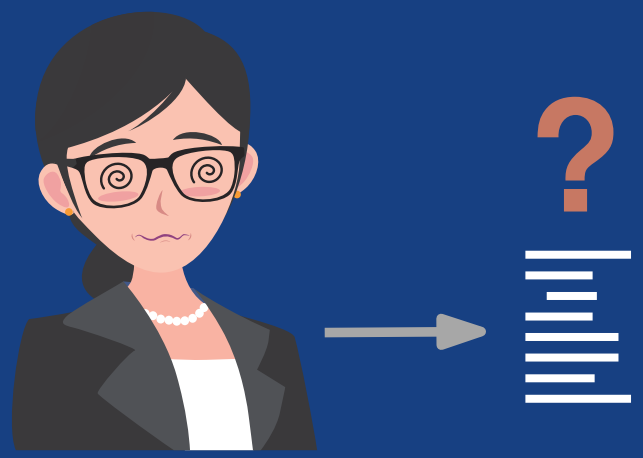

Is this class thread-safe?

Thread-Safe Classes

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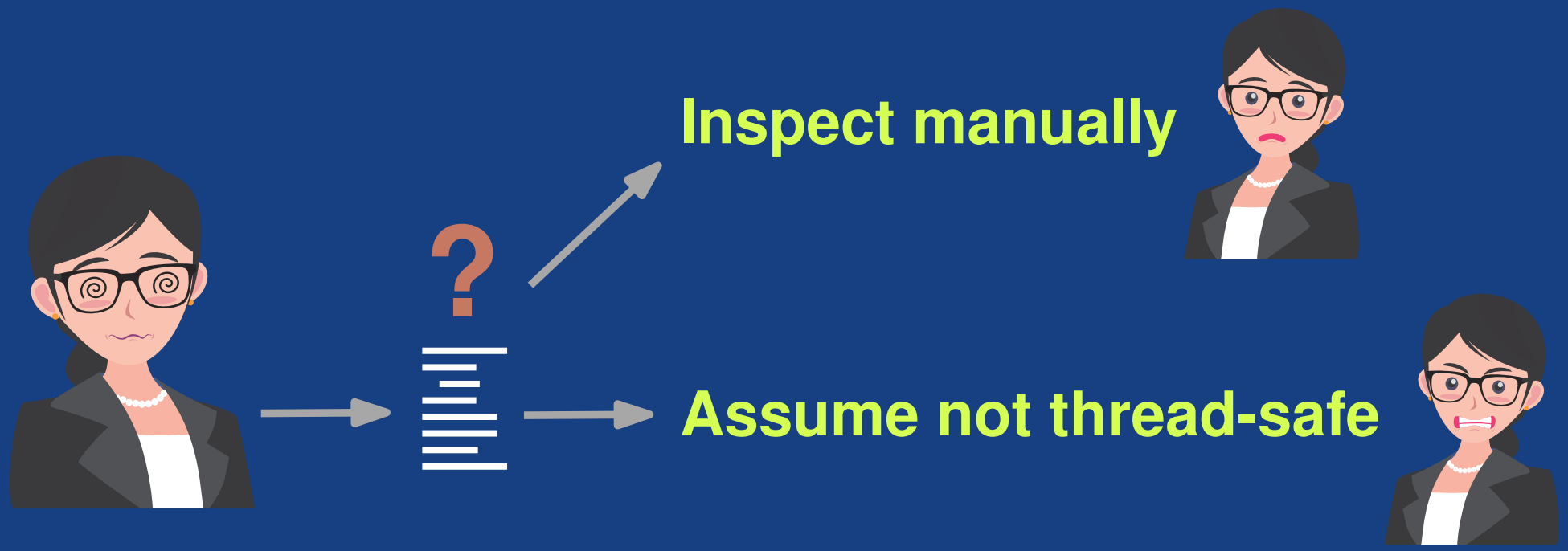

Is this class thread-safe?

Thread-Safe Classes

Inspect manually

Assume not thread-safe

Assume thread-safe

Is this class thread-safe?

Documentation of Thread Safety

Case study: The Qualitas Corpus

- **112 Java projects**
- **179,239 classes**

Documentation of Thread Safety

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- **Search: "concu", "thread", "sync", "parallel"**
  - 8,655 search hits
  - Randomly sample 120 hits
  - Manually inspect random sample

Documentation of Thread Safety

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Documented as:	Count	%
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No documentation	95	79.2%
Total inspected classes	**120**	**100.0%**

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By extrapolation:

% of documented classes in corpus = 1.004%

Is This Class Thread-Safe?

Given an object-oriented class with unknown multi-threading behaviour, infer whether it is supposed to be thread-safe or not

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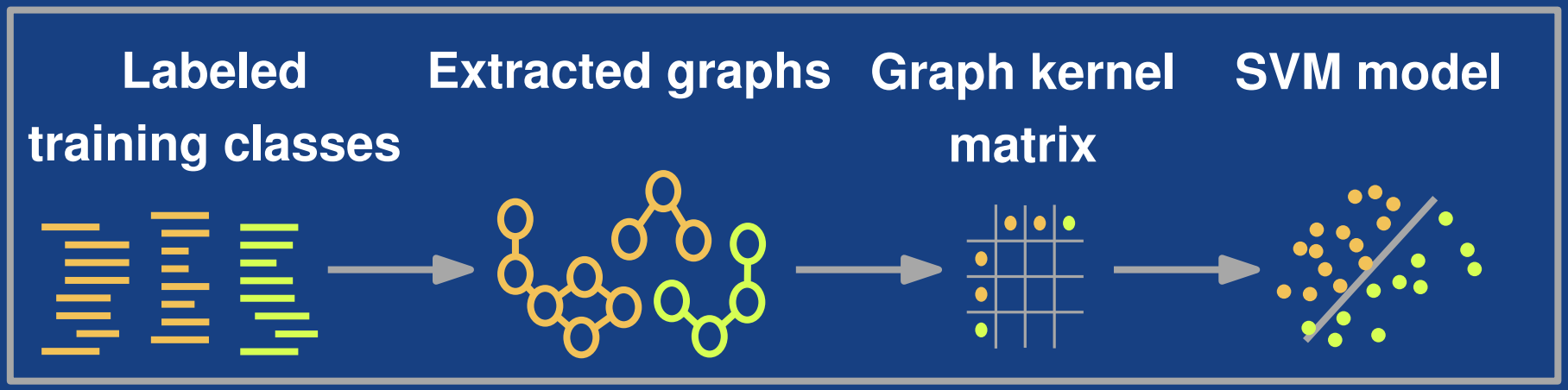
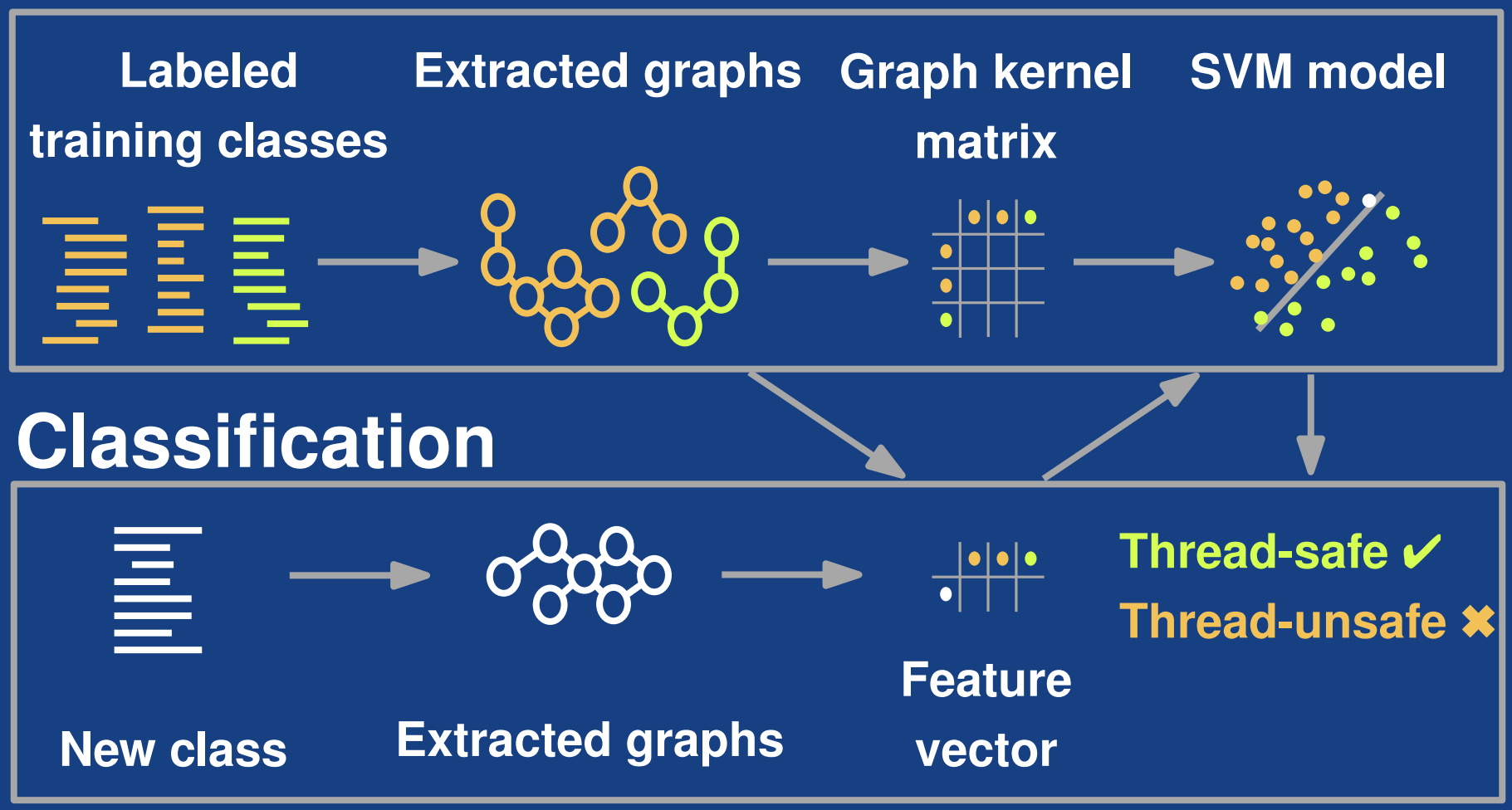
TSFinder: Machine learning-based approach to infer thread safety documentation

Overview of TSFinder

Training



Overview of TSFinder



Field-Focused Graphs

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public class Sequence {

}
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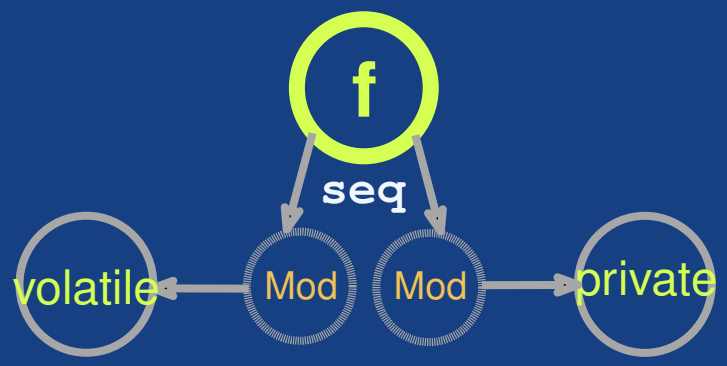


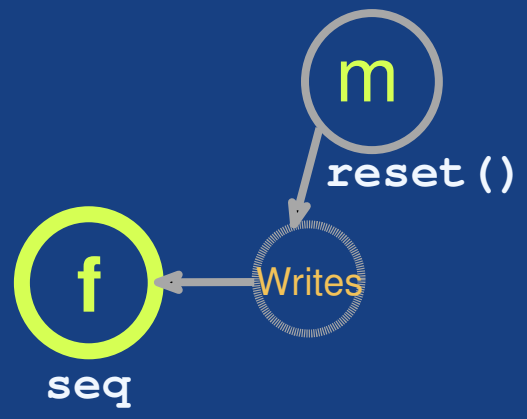

```
}
```

Mod: Modifier

Field-Focused Graphs

```
public class Sequence {
  private volatile int seq;

  void reset() {
    seq = 0;
  }
}
```

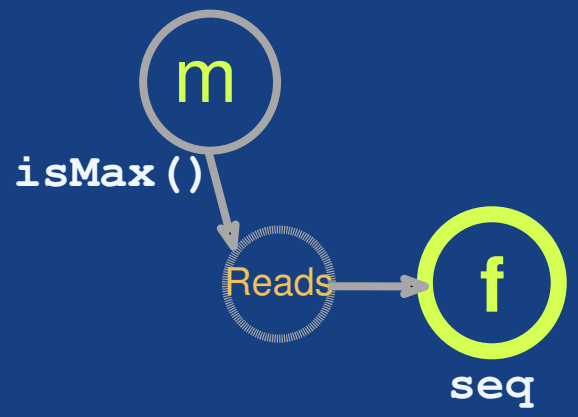


Field-Focused Graphs

```
public class Sequence {
  private volatile int seq;

  boolean isMax() {
    return seq > MAX;
  }

}
```

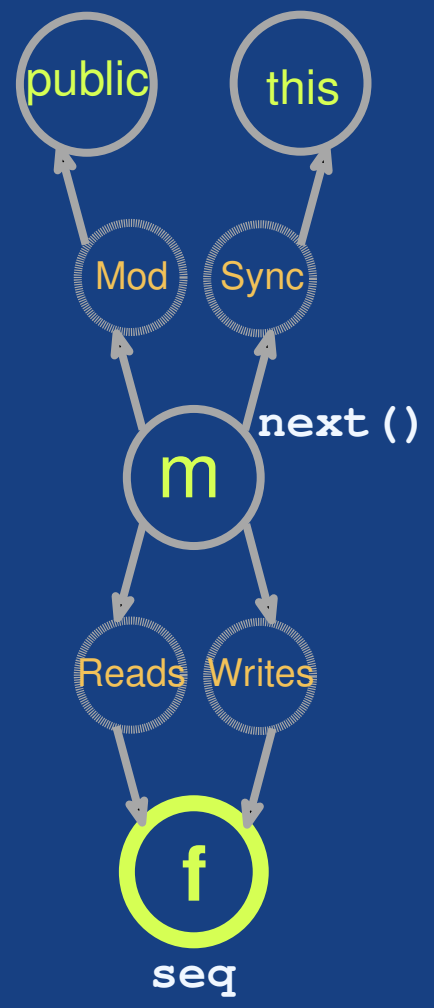


Field-Focused Graphs

```
public class Sequence {
  private volatile int seq;

  synchronized
  public int next() {
    if(!isMax())
      return seq++;
    return -1;
  }

}
```



Field-Focused Graphs

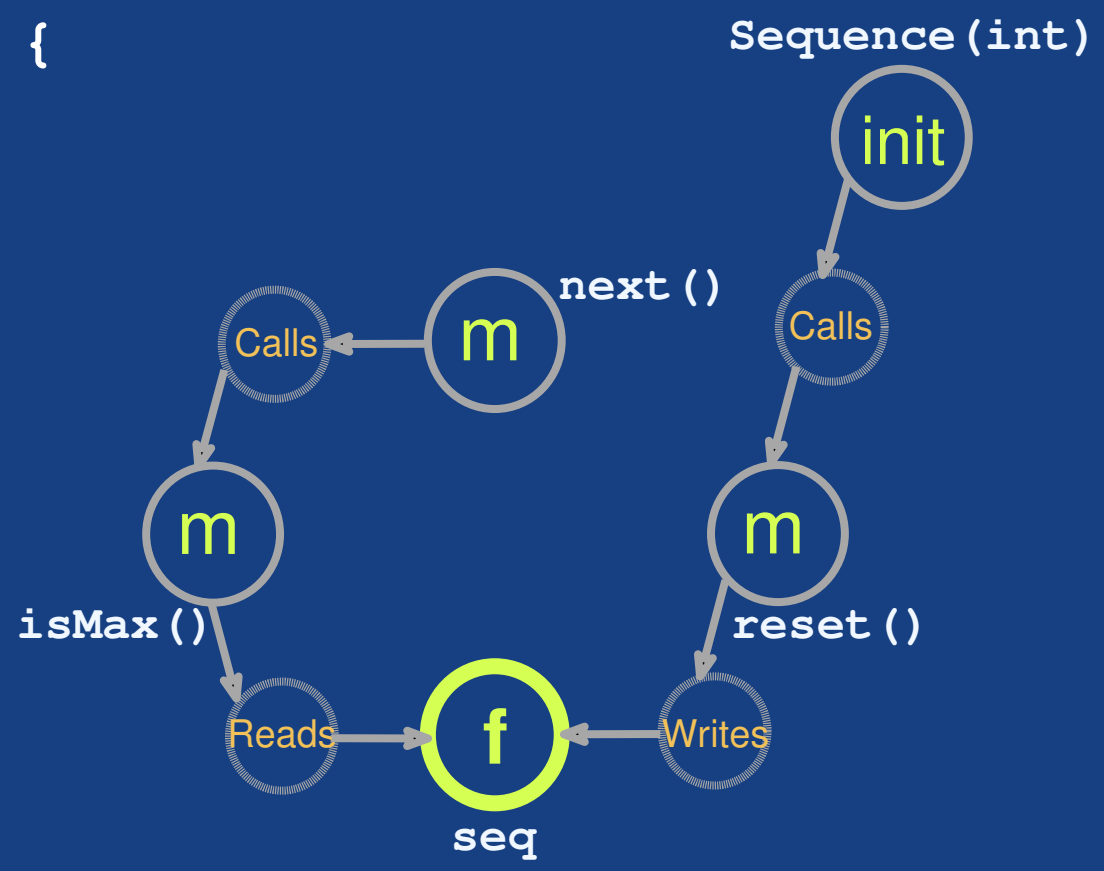
```
public class Sequence {
  private volatile int seq;

  public Sequence(int m) {

    reset();
  }
  synchronized
  public int next() {
    if(!isMax())


  }

}
```



Field-Focused Graphs

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public class Sequence {
  private volatile int seq;
  private int MAX;
  public Sequence(int m) {
    MAX = m;
    reset();
  }
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  public int next() {
    if(!isMax())
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  }
  boolean isMax() {
    return seq > MAX;
  }
  void reset() {
    seq = 0;
  }
}
```

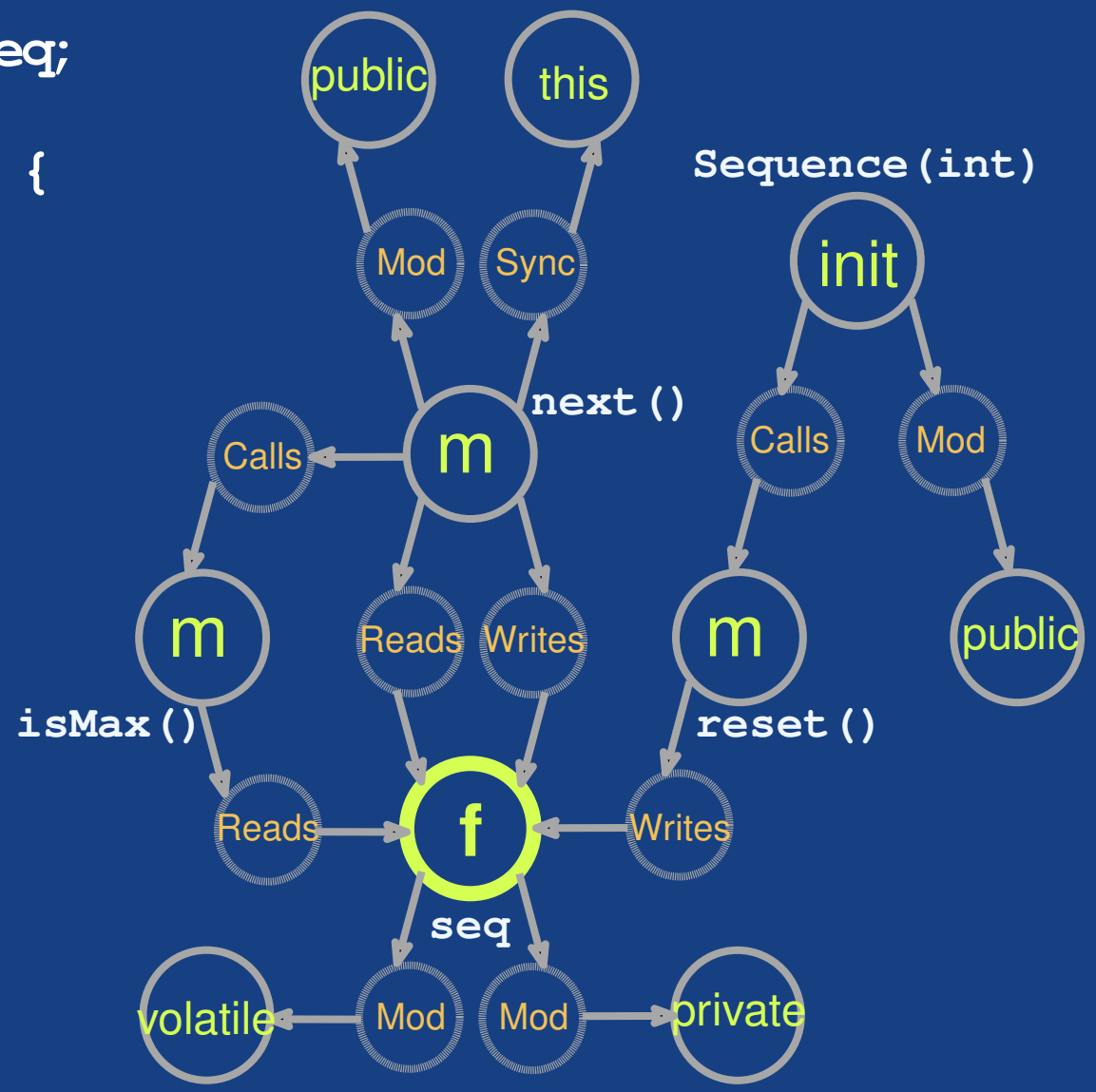

Mod: Modifier

Class to Vector

Known classes

New class C

Class to Vector

Known classes

New class C

Graph kernel:[1] $K($  ,  $) = k \in [0, 1]$

Similarity score

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Known classes

New class C

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Summary of similarity of C to known classes

Vector representation of class C

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Effectiveness of TSFinder

- 230 JDK classes with documented thread safety (balanced number of examples)
- Two-class SVM with SGD[1] and hinge loss
- 10-fold cross-validation

1 Stochastic gradient descent

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Accuracy	**Prec.**	**Rec.**	**Prec.**	**Rec.**
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Most predictions are correct!

1 Stochastic gradient descent

TSFinder Against Baseline

Naive classifier using simple class feautres, e.g.:

- % of volatile fields
- % of synchronized methods

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1 Stochastic gradient descent
2 Sequential minimal optimization

Our Contributions

- State of the practice for documenting thread safety is poor
- New program representation: Field-focused graphs
- TSFinder uses machine learning to infer documentation
- TSFinder infers thread safety documentation with accuracy of 94.5%

Cross-checking documentation against observed exceptional runtime

(Chapter 4)

How to Judge Observed Behavior?

Invocation:

```
commons.lang3.StringUtils.unwrap("a", "a");
```

Observed behavior:

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Exception in thread "main"
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Is this the correct behavior?

No, w.r.t. documentation

Overview of DocRT

- Classify observed exceptional behavior based on documentation

Overview of DocRT

Classify observed exceptional behavior based on documentation

Runtime Behavior
+
Documentation

→ DocRT →

Correct ✔
Buggy ✖

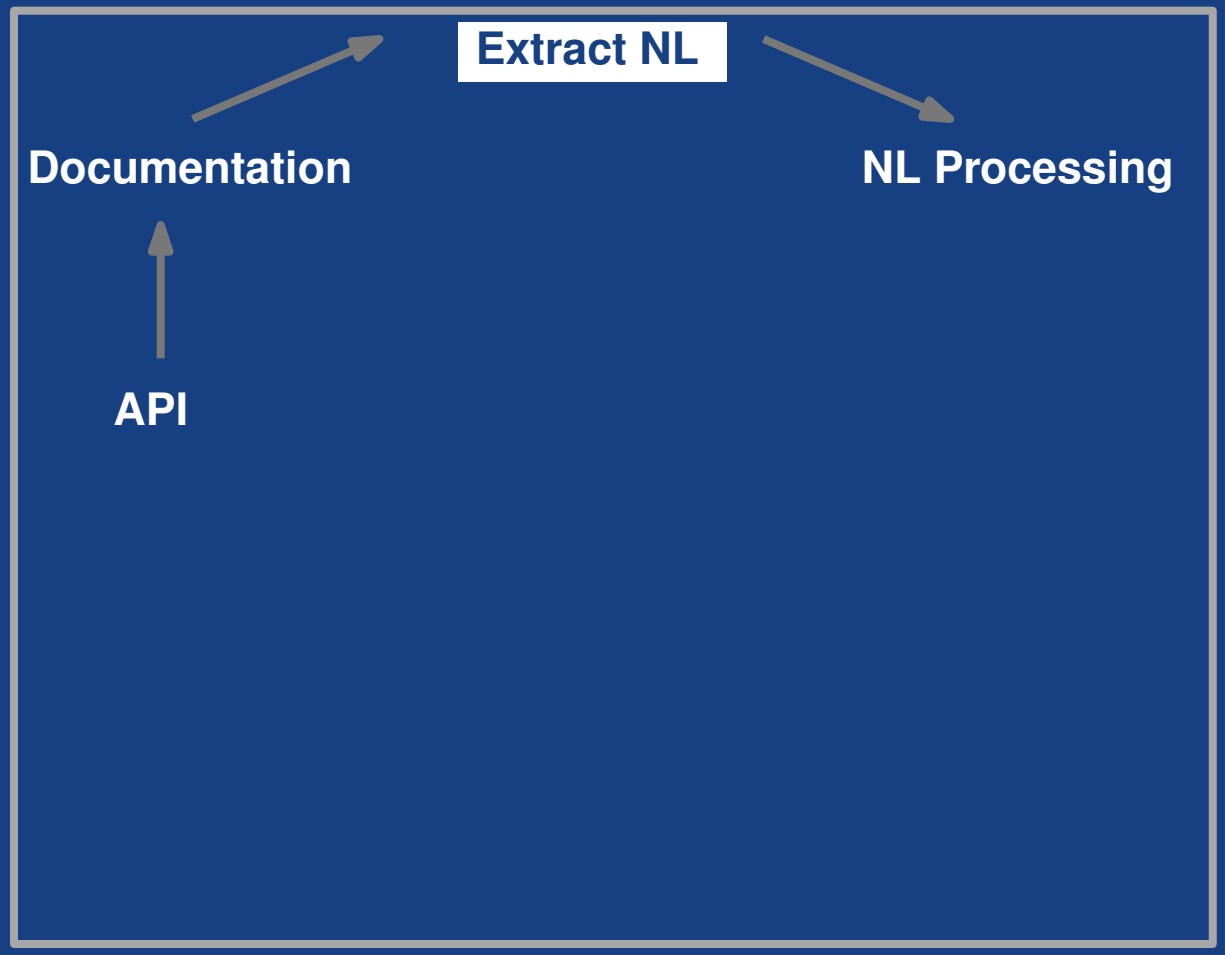
Overview of DocRT

Data Generation

API

Overview of DocRT

Data Generation



Overview of DocRT

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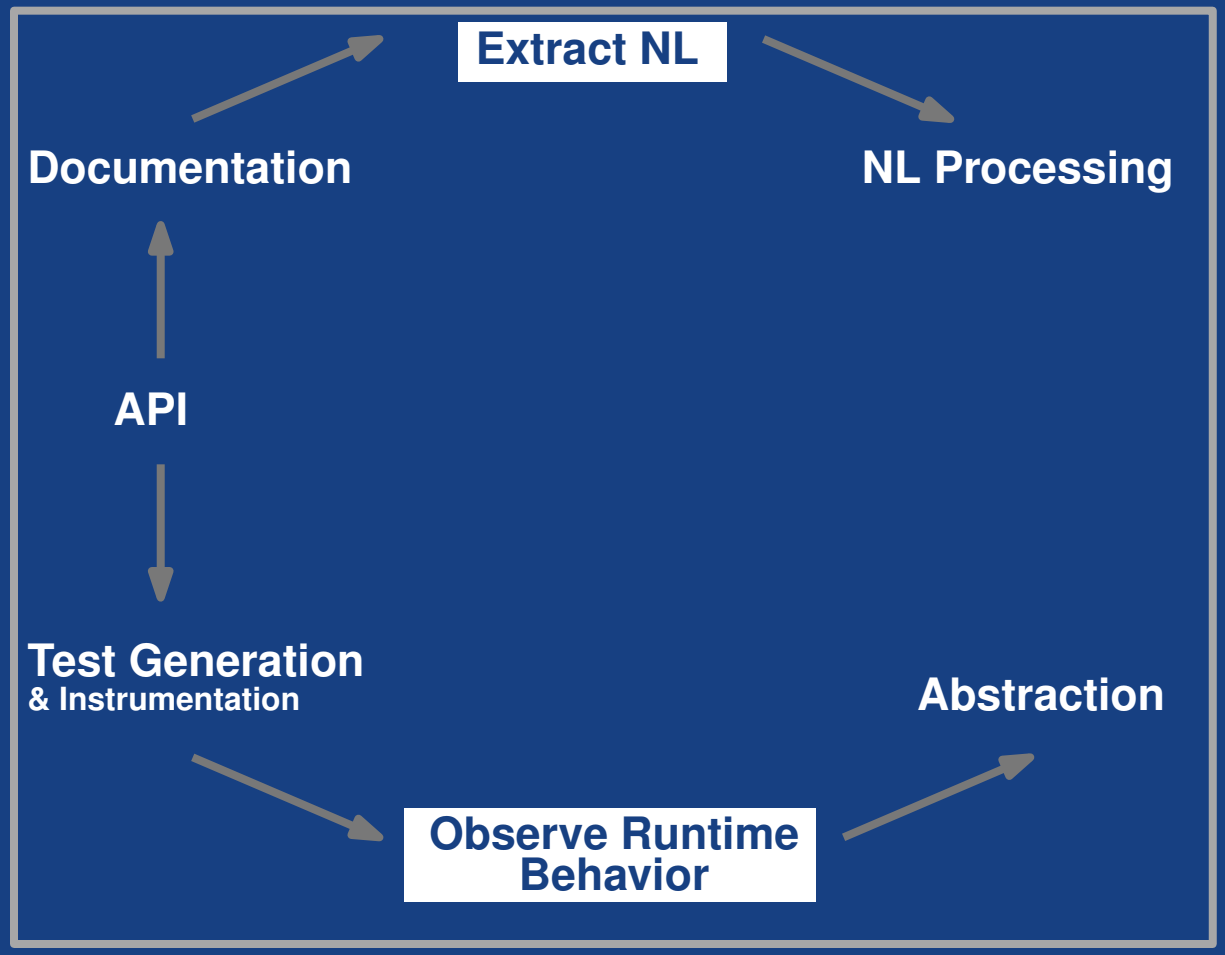

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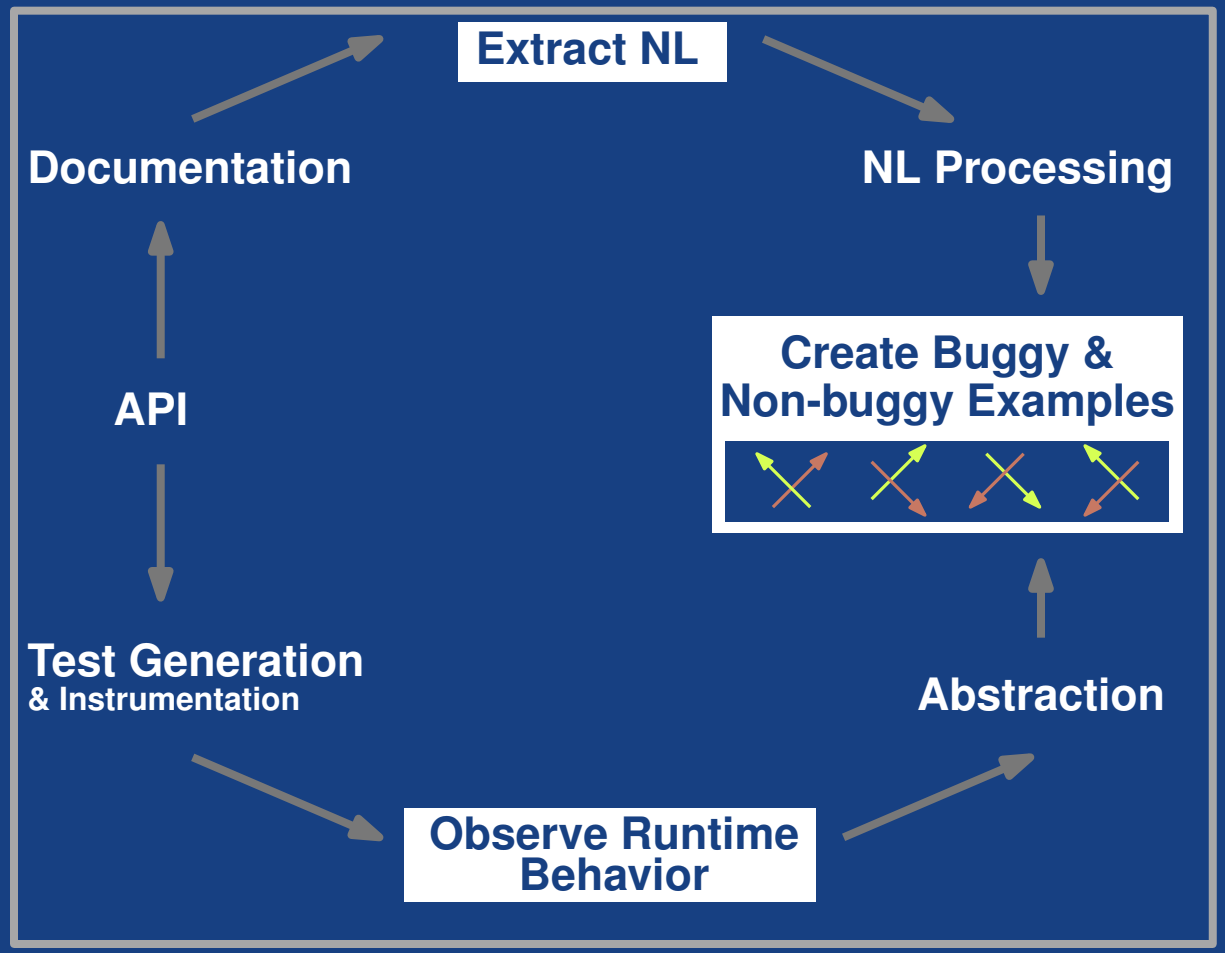

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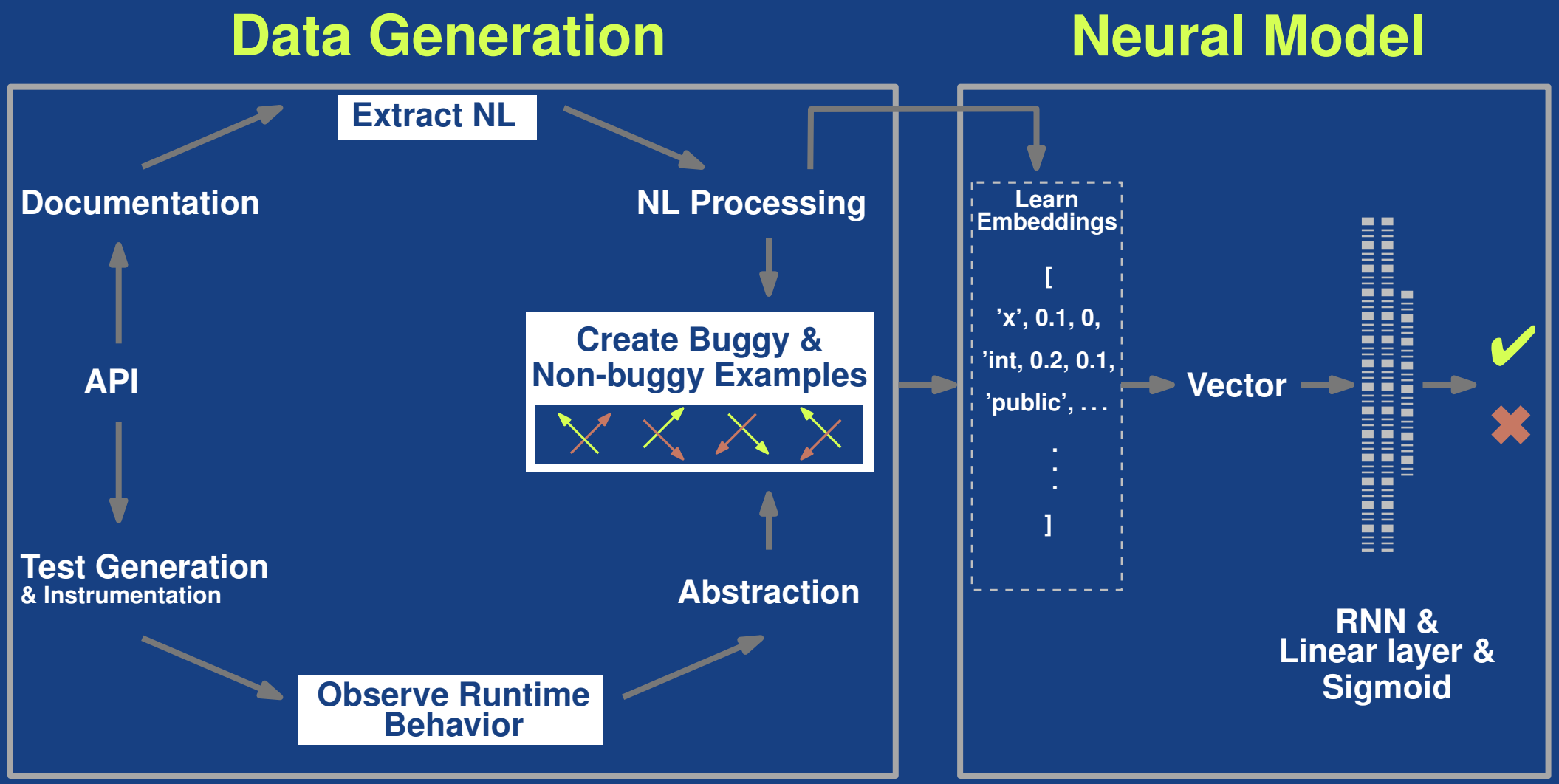

Extracting NL Information

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Names of the method & its parameters

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Types of return value & parameters & exceptions

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NL Descriptions

the method & its paramaters & return value & exceptions

Extracting Runtime Information

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Abstract behavior through:

Pre- & Post-states

- Base object
- Arguments

Result

- Return value
- Thrown exception

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Runtime Exception:

`java.lang.StringIndexOutOfBoundsException`

How to Obtain Buggy Examples?

- **Assume all collected pairs of documentation and behavior are correct.**

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- **Assume all collected pairs of documentation and behavior are correct.**
- **Mutate the collected pairs.**

  Behavior mutations:

  - Raise random exception
  - Remove thrown exception
  - Replace thrown exception by random one

  NL mutations:

  - Remove thrown exception from documentation

How to Obtain Buggy Examples?

- **Assume** all collected pairs of documentation and behavior **are correct**.

Invocation:

```
commons.lang3.StringUtils.unwrap("xyx", "x");
```

Observed behavior: return value: `"y"`

Correct example

Mutation: Raise random exception

How to Obtain Buggy Examples?

- **Assume** all collected pairs of documentation and behavior **are correct**.

Correct example

Invocation:

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Observed behavior: return value: `"y"`

Mutation: Raise random exception

Buggy example

Invocation:

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Observed behavior:

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  java.lang.NullPointerException
```

Evaluation: Setup

- **5,000 Java projects from Maven**
- **207,455 Public methods with doc**
- **Randoop**[1] generates 146,397 tests for 25,076 methods
- **292,782 pairs of buggy & non-buggy method doc. and behavior (almost balanced)**
- **70, 15, 15 % split for training, validation, and testing**

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Training The Neural Model

- Two Bi-directional LSTM layers (size=100)
- Dropout of 0.3
- Batch size of 1k
- 50 epochs
- Train using the Adam optimizer
- Decaying learning rate of 0.0001

Effectiveness of DocRT

On the test set:

Precision: 81%

Accuracy: 87%

Recall: 97%

F1: 88%

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In practice:

18 bugs reports from popular projects, e.g.:

- 11 Undocumented `NullPointerException`
- 3 Unexpected `IndexOutOfBounds` in corner cases
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- 1 Undocumented `IllegalArgumentException`

DocRT detects all of them.

Detecting New Bugs

Sample top 50 buggy predictions in the test set

Analyzed method calls	21,592
Calls where DocRT reports a warning	4,829
Inspected calls with warning	50
True positives	45
Undocumented exception	39
Wrong type of exception documented	1
False positives	5
Indirect description of the exceptional behavior	4
Exceptional behavior is fully documented	1

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Detecting New Bugs: Example

Documentation:

```
public byte byteAt(int i)
Gets a byte within this sequence of bytes
Parameters:
i - index into sequence
Returns:
byte
Throws:
IllegalArgumentException - if i is out of range
```

Invocation:

```
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                                org.apache.fluo.api.data.Bytes();
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Observed behavior:

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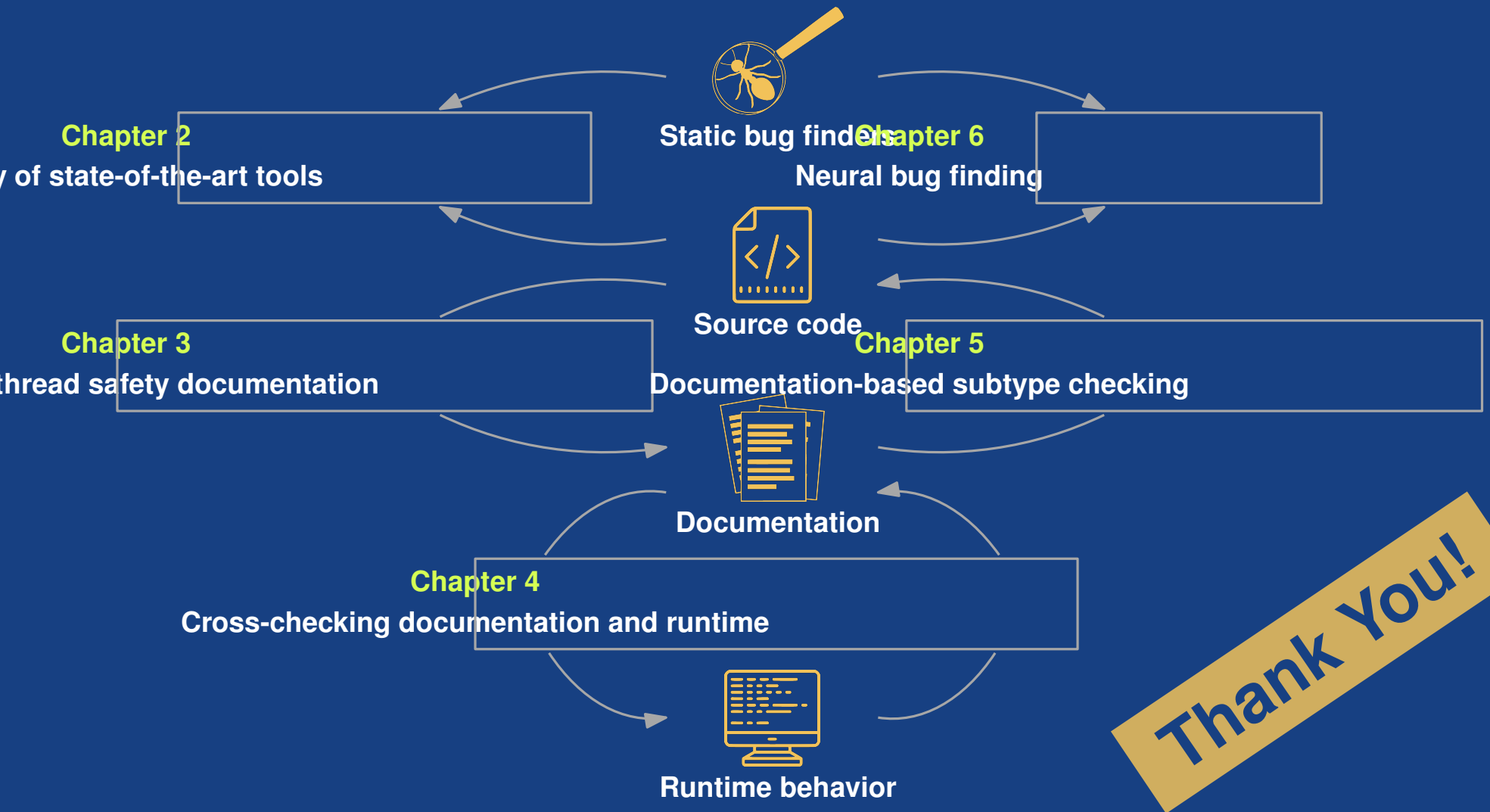
Our Contributions

- Novel learning task for the test oracle problem
- DocRT leverages documentation to check runtime behavior
- DocRT detects inconsistent documentation w.r.t. runtime behavior with accuracy of 87%

Learning from Programs & their Documentation



Thank You!

Characters images from Freepik, https://www.freepik.com/

Future Work

- **Utilizing documentation in more SE tasks**
  e.g., in program repair
- **Extracting and utilizing more domain-knowledge from other NL sources**
  e.g., bug reports, issue trackers, commit messages
- **Richer source code representation for ML-based SE tasks**
- **Abstraction (representation) of runtime behavior**
- **Learning from runtime**

Publications

- Andrew Habib and Michael Pradel. *How many of all bugs do we find? a study of static bug detectors.* IEEE/ACM International Conference on Automated Software Engineering (ASE) 2018.
- Andrew Habib and Michael Pradel. *Is this class thread-safe? inferring documentation using graph-based learning.* IEEE/ACM International Conference on Automated Software Engineering (ASE) 2018.
- Andrew Habib, Avraham Shinnar, Martin Hirzel, and Michael Pradel. *Type Safety with JSON Subschema.* CoRR abs/1911.12651 (2019).
- Andrew Habib and Michael Pradel. *Neural Bug Finding: A Study of Opportunities and Challenges.* CoRR abs/1906.00307 (2019).