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Efficient Analysis using Soufflé

An Experience Report.

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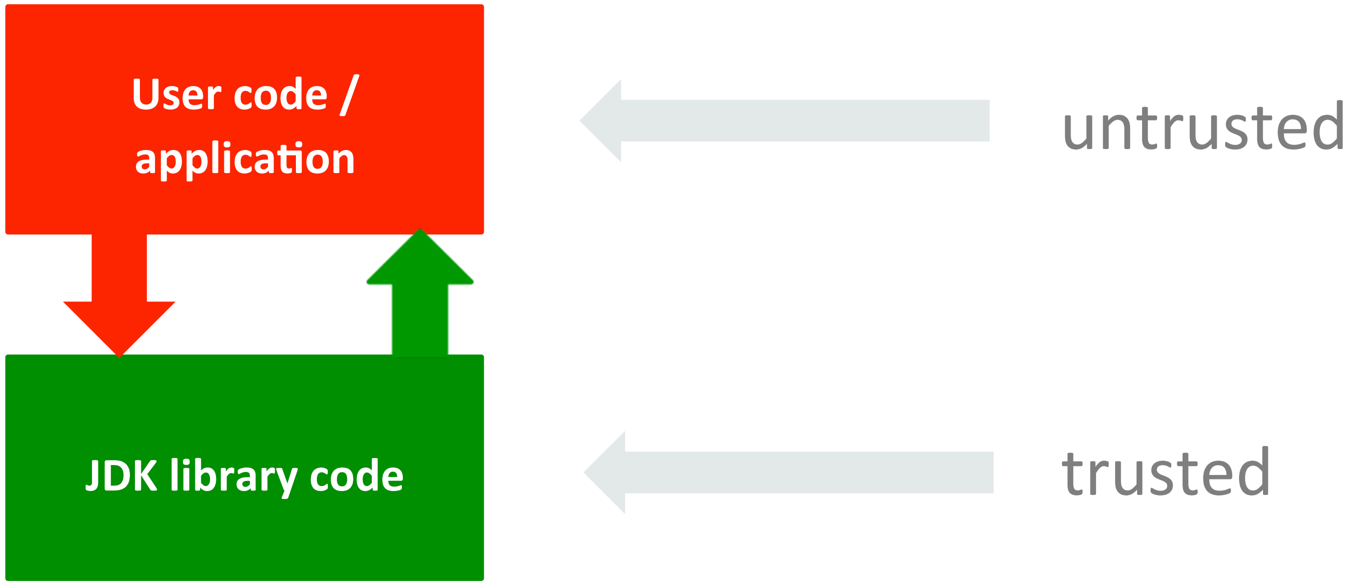
Aim: To analyse the JDK for vulnerabilities using analyses encoded in Datalog

Open World Analysis

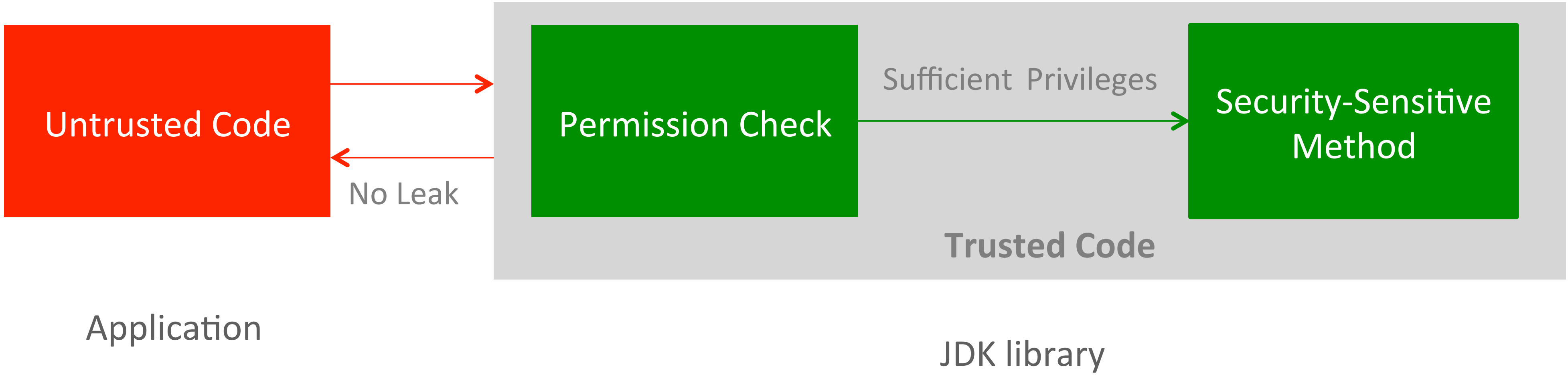
[SOAP’15 – Combining Type-Analysis with Points-To Analysis for Analyzing Java Library Source-Code]



Analysis of libraries, rather than complete applications

Unguarded Caller-Sensitive Methods

[SOAP’15 – Understanding Caller-Sensitive Method Vulnerabilities]



Existing Datalog Engines

DOOP context-**insensitive** points-to analysis over OpenJDK 7
w/o open world w/call graph construction on the fly

Tool	Time	Memory
BDDBDDB	30 minutes	5.7GB
mZ (Z3)	✘	✘
LogicBlox	20 minutes	100 GB

On Intel Xeon E5-2660 (2.2 GHz) machine with 256 GB RAM
Time out set to 24 hours

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Problem Size – OpenJDK 7 b147

Program Element	Size
Variables	1.5 Million
Allocation Sites (heap objects)	361 Thousand
Methods	160 Thousand
Invocation Sites	590 Thousand
Types	17 Thousand
Size of CI Points-To Set	**866 Million**

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With Soufflé

DOOP context-**insensitive** points-to analysis over OpenJDK 7
w/o open world w/call graph construction on the fly

Tool	Time	Memory
BDDBDDB	30 minutes	5.7GB
mZ (Z3)	✘	✘
LogicBlox	20 minutes	100 GB
Soufflé	40 seconds	7.5 GB

On Intel Xeon E5-2660 (2.2 GHz) machine with 256 GB RAM
Time out set to 24 hours

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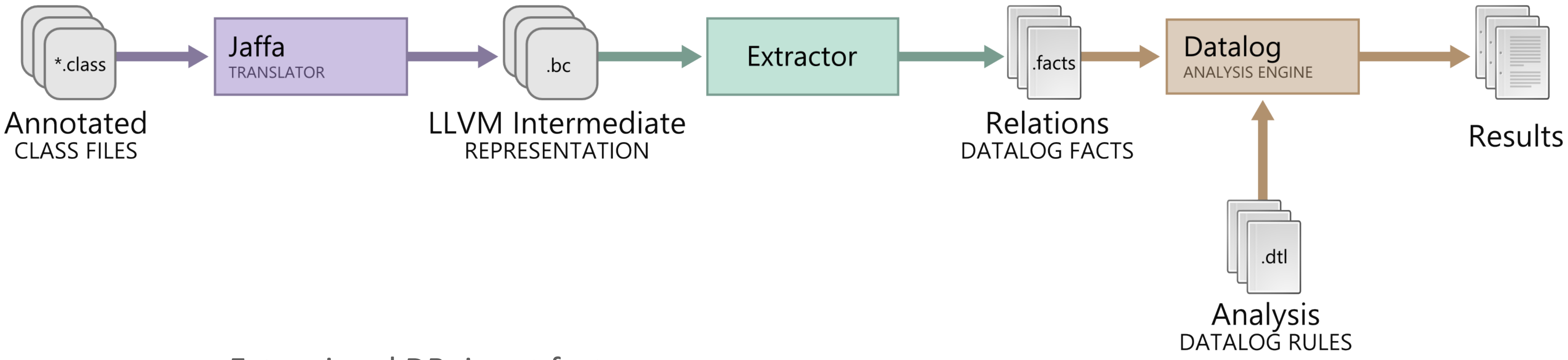
The Soufflé Datalog Compiler

The Soufflé Framework



Extensional DB: input facts
Intensional DB: Datalog rules

Problem Size – OpenJDK 7 b147

Program Element	Size
Variables	1.5 Million
Allocation Sites	361 Thousand
Methods	160 Thousand
Invocation Sites	590 Thousand
Types	17 Thousand
Size of CI Points-To Set	**866 Million**
EDB (text, in-memory)	**3.6GB, 872MB**
EDB # facts	**16,810,032**

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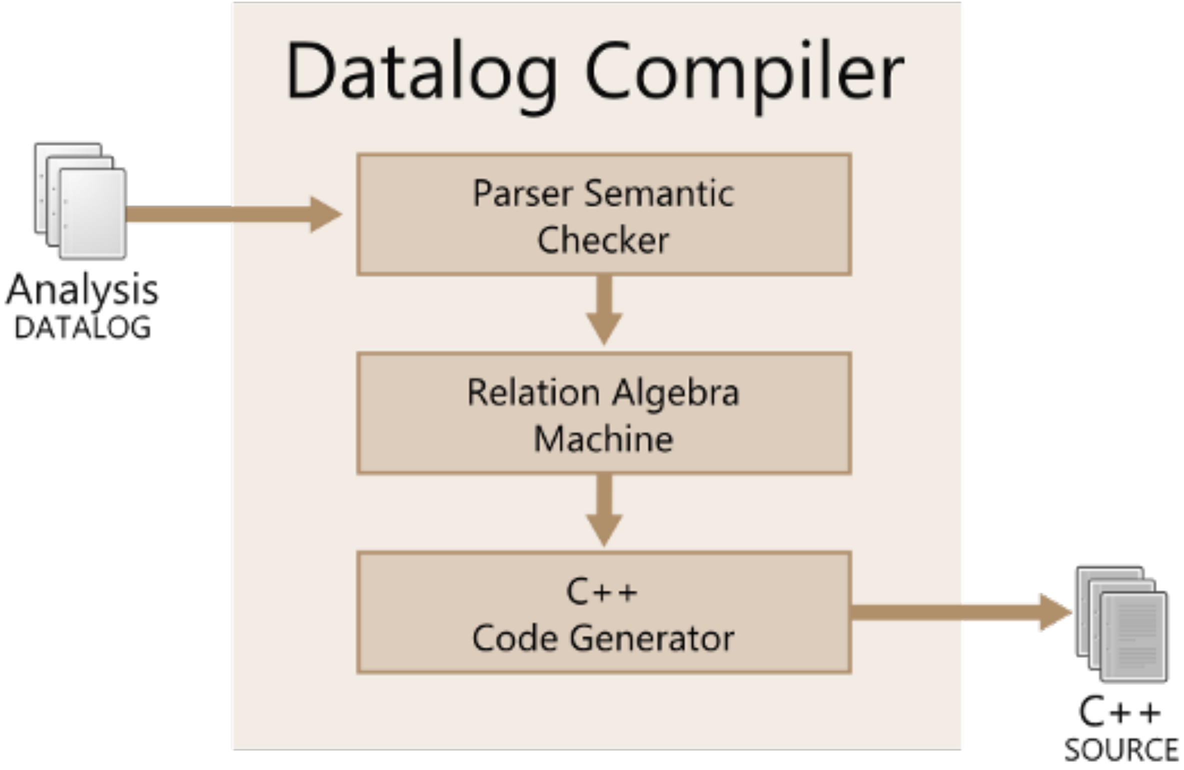
Soufflé Key Contributions

1. Staged compilation
2. Auto-index selection
3. Brie data structure

1- Staged Compilation

[CAV'16 – Soufflé: On Synthesis of Datalog for Program Analyzers]

- Efficient semi-naïve evaluation
  - Elimination of copying overheads: single merge operation
- Relational Algebra Machine
  - Performs relational algebra operations & fixed-point calculations; fixed tables
- Translate abstract machine program to C++ code
  - Generate specialised OpenMP/C++
  - Execution in memory



2- Auto Index Selection

- Index to speed up searches in tables for equi-joins
  - Example: {(x,y,z) in A |A.x = “p” ∧ A.y = “q”}
  - Search denoted by columns {x,y}
- Index: total order via lexicographical order on column
  - Example: x < y < z
- An index may cover more than one search
- Prefix sets of lexicographical order constitute valid searches
  - Example x < y < z => {x}, {x,y}, {x,y,z}
- Maximum Matching solves optimal index selection problem in P
  - Application of Dilworth’s theorem

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2- Auto Index Selection – Experiment, OpenJDK 7

Exhaustive index selection vs. optimal auto index selection with reuse

	Runtime (min)	Memory (GB)
No auto-index, CI	16:30	81.8
Auto-index, CI	0:42	10.3
No auto-index, CS	*	*
Auto-index, CS	5h, 30 min	18.9

* Timed out after running for 4 days using 55 GB

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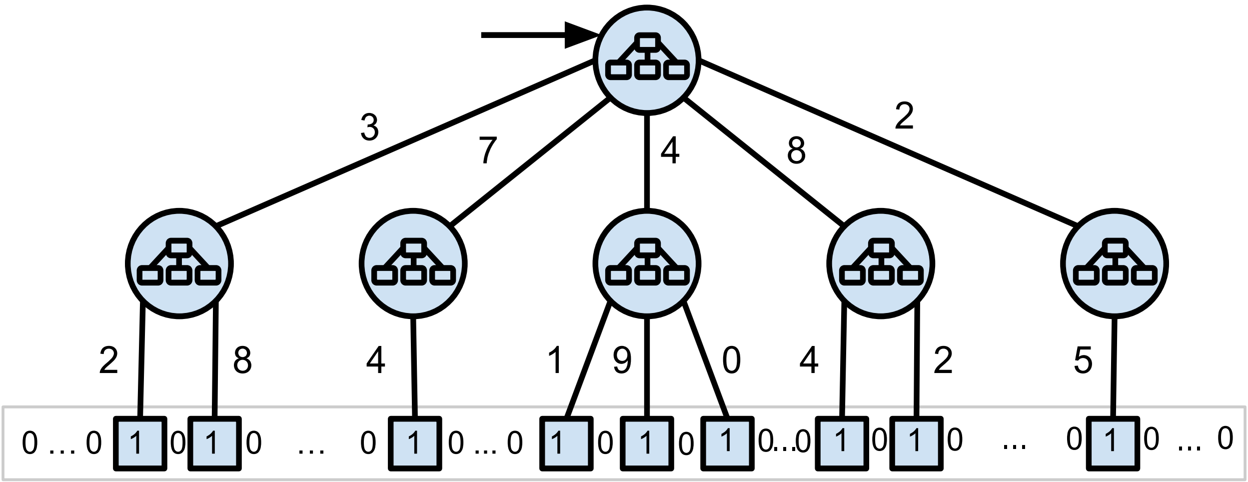
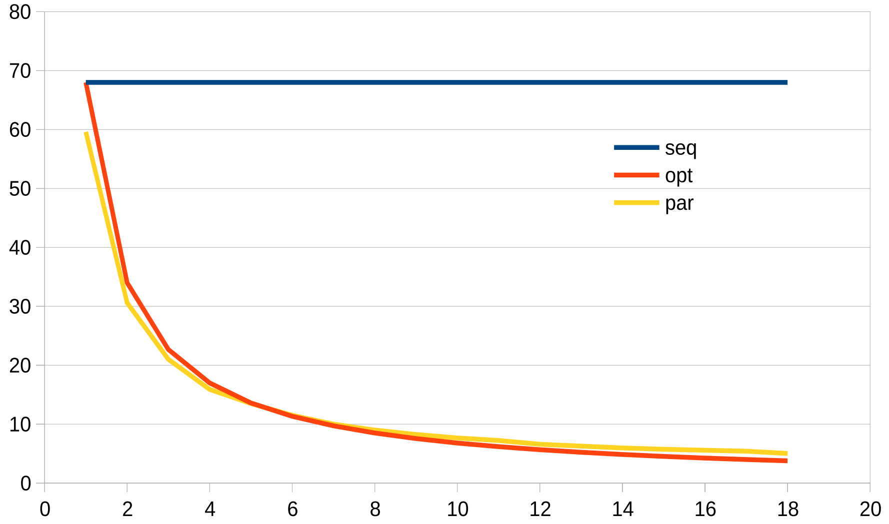
3- Brie Data Structure for Binary Relations in Soufflé





- Hybrid data structure as a fixed-depth Trie with sparse bitmaps
  - Nearly lock-free
  - Use of geometric encoding
  - Becomes scalable for large amount of data (but only binary relations)

Exploratory Work before Soufflé

[ASWEC'15 – A Datalog Source-to-Source Translator for Static Program Analysis: An Experience Report]

- Datalog to SQL translator
  - using a relational database as back-end for evaluating Datalog rules
- Various SQL optimisations
- Insufficient for large data
  - Insensitive points-to for OpenJDK analysis too slow (~8h)

Soufflé – Lessons Learned

- Compilation vs synthesis
  - ✔ Use of program synthesis
  - ✖ Use of relational database to evaluate Datalog rules
- Insights into semi-naïve algorithm
  - ✔ Distinct read and write phases
  - ✖ Copying tables to keep track of **previous**, **current**, **delta** and **new** relations
- Use of cache-sensitive, in-memory data structures is vital
  - ✔ B-Trees, geometric encoding of sets and binary relations
  - ✖ Bloom filters, hash-tables: demands sparseness which increases memory usage
- Parallelisation
  - ✔ Optimistic locking of B-trees during insert
  - ✖ Locking potentially maximal subtree

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Performance Improvements Over Time

DOOP context-insensitive points-to: OpenJDK 7 w/o call-graph construction

Versions	Runtime
SQL Source-to-source translation	~8h
RAM / Hashtables	~8h
RAM / Google B-Trees	~3h
Compiler / C++ Templates for Index Order	15m
+ Auto Index	10m
+ Fast B-Tree & Indexed Tables	2m 40s
+ Tries	<1m

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Context-Sensitive 2O1H Points-To Analysis Over OpenJDK 7

[CC'16 – Staged Points-to Analysis for Large Code Bases]

Tool	Time	Memory
BDDBDDB	✘	✘
mZ (Z3)	✘	✘
LogicBlox	✘	✘
Soufflé	4.5 hours	186 GB

On Intel Xeon E5-2660 (2.2 GHz) machine with 256 GB RAM
Time out set to 24 hours

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Soufflé is Open Source

https://github.com/oracle/souffle/

https://github.com/souffle-lang/

- Listen to a preview of the CAV'16 presentation:
  - https://youtu.be/8WM0im4RV7M, "An Experience Report: Efficient Analysis using Souffle", Bernhard Scholz, University of Sydney, 8th July 2016

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The Soufflé Datalog compiler provides high performance in program analysis and scales well to the JDK codebase

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0-Day Exploit Example: CVE-2012-4681

Public method in sun.awt.Toolkit

```
public static Field getField(final Class klass,
                             final String fieldName) {
  return AccessController.doPrivileged(
     new PrivilegedAction<Field>() {

       public Field run() {

         try {

           Field field = klass.getDeclaredField(fieldName);

           field.setAccessible(true);

           return field;

         } ... }}}
```

Points-to Analysis: 2-Type-Sensitive + Heap

Closed vs open world over rt.jar

Assumption	Runtime	# VarPointsTo Facts
Closed world	1:10 hour	~200 million
Open world	14 hours	~1 billion

Missing out on many inputs and outputs from/to untrusted code