Advanced Static Analysis of Atomicity in Concurrent Programs through Facebook Infer

Master's Thesis

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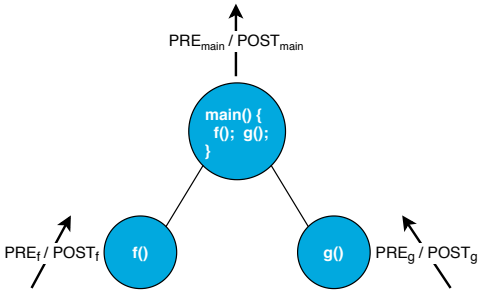
- Detecting and checking desired atomicity of function call sequences.
  - Often required in concurrent programs.
  - Violation may cause nasty errors.

```
void invoke(char *method) {
  ...
  if (server.is_registered(method)) {
    server.invoke(method);
  }
  ...
}
```

The sequence of **is_registered** and **invoke** should be executed atomically.

If not locked, the method can be unregistered by a concurrent thread.

- Open-source static analysis framework for interprocedural analyses.
  - Based on abstract interpretation.
- Highly scalable.
  - Follows principles of compositionality.
  - Computes function summaries bottom-up on call-trees.
- Supports C, C++, Java, Obj-C, C#.



Atomer: Atomicity Violations Analyser

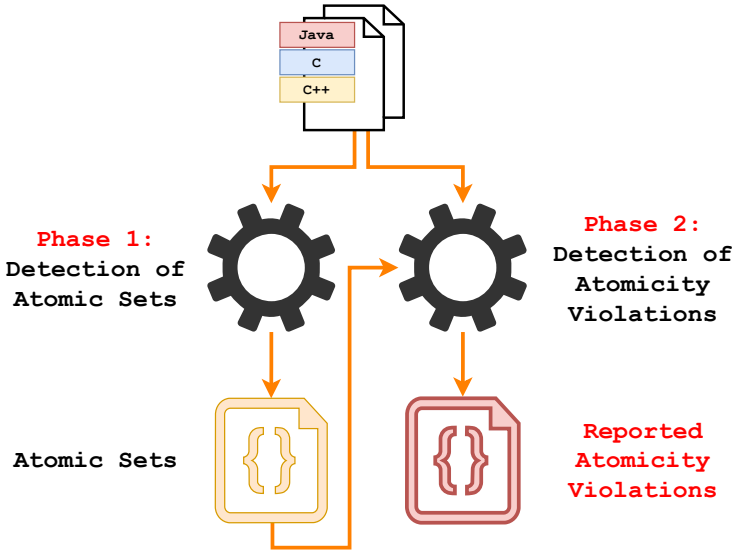
- Facebook Infer plugin created within the author's BSc thesis:

  HARMIM, D. *Static Analysis Using Facebook Infer to Find Atomicity Violations*. Brno, 2019. Bachelor's thesis. Brno University of Technology, Faculty of Information Technology. Supervisor VOJNAR, T.

- **Assumption**: call sequences executed atomically once should (probably) be executed always atomically.
- Implemented for C programs that use PThread locks.
- Limited scalability on extensive codebases.
- Reports many false alarms when analysing real-life code.

High-Level Analysis Process



Phases of the Analysis (Approximation with Sets)

1. Detection of atomic call sets.
   - Approximates sequences by sets.
   - **Summary**: $\chi \in 2^{\Sigma} \times 2^{2^{\Sigma}}$ (set of all calls, set of atomic call sets)

```
void f() {
  lock(L);
  x(); y(); z(); // x.y.z -> {x,y,z}
  unlock(L);
  a();
  lock(L);
  z(); y(); x(); // z.y.x -> {x,y,z}
  unlock(L);
}
```

$\chi_{\mathtt{f}} = (\{\mathtt{a}, \mathtt{x}, \mathtt{y}, \mathtt{z}\}, \{\{\mathtt{x}, \mathtt{y}, \mathtt{z}\}\})$

$\chi'_{\mathtt{f}} = (\mathtt{x} \cdot \mathtt{y} \cdot \mathtt{z} \cdot \mathtt{a}, \{\mathtt{x} \cdot \mathtt{y} \cdot \mathtt{z}, \mathtt{z} \cdot \mathtt{y} \cdot \mathtt{x}\})$

2. Detection of atomicity violations.
   - Derives "atomic pairs" from the first phase: $\Omega \in 2^{\Sigma \times \Sigma}$
   - Looks for non-atomic pairs of calls assumed to run atomically.
   - **Summary**: $\chi \in 2^{\Sigma \times \Sigma}$ (set of atomicity violations)

```
void g() {
  a(); x(); y(); b();
}
```

$\Omega = \{(\mathtt{x}, \mathtt{y}), (\mathtt{x}, \mathtt{z}), (\mathtt{y}, \mathtt{x}), (\mathtt{y}, \mathtt{z}), (\mathtt{z}, \mathtt{x}), (\mathtt{z}, \mathtt{y})\}$

$\Omega' = \{(\mathtt{x}, \mathtt{y}), (\mathtt{y}, \mathtt{z}), (\mathtt{z}, \mathtt{y}), (\mathtt{y}, \mathtt{x})\}$

$(\mathtt{x}, \mathtt{y}) \in \Omega \Longrightarrow \chi_{\mathtt{g}} = \{(\mathtt{x}, \mathtt{y})\}$

Further Atomer's Enhancements

- Support for C++ and Java.
  - Working with advanced locks: re-entrant locks, monitors, lock guards, etc.
- Distinguishing different lock instances.
  - Approximating lock objects using syntactic access paths — a representation of heap locations via the paths used to access them.
- Analysis's parametrisation:
  - ignoring generic functions versus concentrating on critical functions;
  - limiting the number of calls or the depth of nested calls in critical sections.

Experimental Evaluation

- Scalability evaluated on 54 real-life complex C programs.
  - 806,431 LOC in total.
- Double acceleration in average.

	v1.0.0		v2.0.0	
	Phs. 1	**Phs. 2**	**Phs. 1**	**Phs. 2**
Avg. Time (s)	70.98	109.11	37.96	50.93
Total Time (s)	4,117	5,892	2,164	2,750

- Experiments with Apache Cassandra and Apache Tomcat (both $\sim$250 KLOC).
  - Successfully rediscovered already fixed reported real bugs.
  - The number of reported bugs was significantly reduced ($\sim 4\times$).
  - Still hard to say which of the bugs are real — the accuracy needs to be further improved.

Summary[1]

- Proposed and implemented extensions for Atomer:
  - approximation with sets, support for C++ and Java, distinguishing different lock instances, parametrisation of the analysis.
- Successfully tested and experimentally evaluated.
  - Both scalability and accuracy were significantly increased.
- Experiments with real-life programs.

Future goals

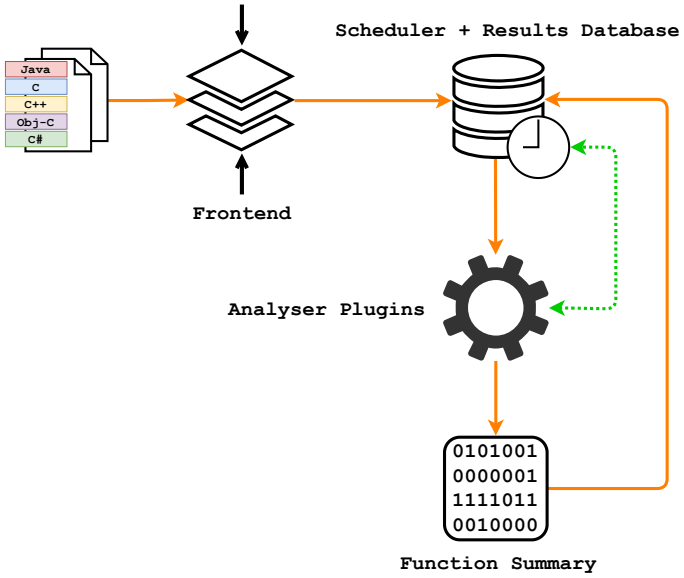
- Further increase accuracy/reduce the number of false alarms.
  - Combining with dynamic analysis.
  - Statistic ranking of atomic functions/reported errors.
  - Considering formal parameters of functions.
  - Machine learning of analysis' parameter values.

[1] The preliminary results of this work were presented at the Excel@FIT'21 (it won two awards). It is supported by the H2020 ECSEL project VALU3S.

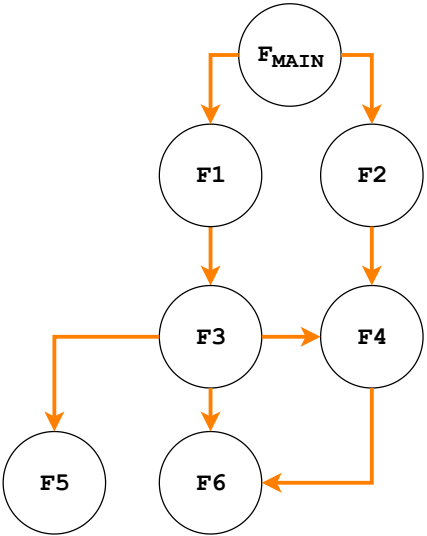
Otázky oponenta

1. **Plánujete podniknout další kroky pro zařazení Atomeru do hlavní větve frameworku Facebook Infer?**
   - Ano, určitě bychom se rádi o zařazení v budoucnu pokusili.
   - Repositář Atomeru je pravidelně aktualizován na nejnovější verzi frameworku.
   - Atomer už byl dříve (úspěšně) prezentován a konzultován s vývojáři Inferu.

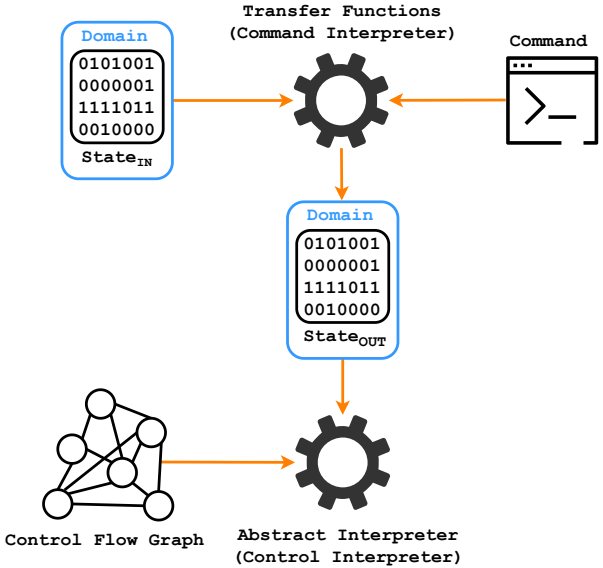
Facebook Infer's Architecture



Demonstration of Facebook Infer's Analysis



Abstract Interpretation in Facebook Infer



Real-life bug in a package `org.apache.catalina.core.StandardContext`

```
public void addParameter(String name, String value) {
  ...
  if (parameters.get(name) != null)
    throw new IllegalArgumentException
      (sm.getString("standardContext.parameter.duplicate", name));

  // Add this parameter to our defined set
  synchronized (parameters) {
    parameters.put(name, value);
  }
  fireContainerEvent("addParameter", name);
}
```

Advanced Manipulation with Locks

- Access path used for a lock's identification: $\pi \in \Pi ::= \mathit{Var} \times \mathit{Field}^*$,
  - *Var* is a set of all variables,
  - *Field* is a set of field names.
- Identification of a critical section: $(\pi, l) \in \Pi \times \mathbb{N}^\top$,
  - π is an access path that identifies a lock object that locks the section,
  - l is the number of locks of the lock object identified by π,
  - $\mathbb{N}^\top$ denotes $\mathbb{N} \cup \{\top\}$,
    - $\top$ represents a number larger than some upper bound $t \in \mathbb{N}$.
- Representation of a lock guard: $(\pi_g, L) \in \Pi \times 2^\Pi$,
  - π_g is is an access path that identifies the lock guard,
  - L is a set of access paths that identify lock objects associated with the guard.