Behavioral Type Inference for Concurrent Object-Oriented Languages

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Problem

Large-scale software systems rely on communication protocols

Mainstream programming languages do not cope with them:

- provide (some) data-type safety
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- provide (some) data-type safety
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Most (static) approaches to code correctness not well suited

- Usual safety guarantees not enough:
  An application that allows to open and close a file, but not read or write, is safe but not useful
- Liveness is hard to statically verify (sometimes not possible)

State-of-the-art

Several approaches to analyse code

- Deductive proof systems
- Model-checkers / Abstract Interpretation
- Type systems

We aim at an *automatic, decidable, tool, coping with safety and (weak) liveness properties* (like protocol completion)

Our language of choice

The Mool Language: `http://gloss.di.fc.ul.pt/mool`

- Small, rigorously defined, Java-like, and object-oriented
- Associates with each class a behavioural type
- Types express valid sequences of method calls
- Type system ensures statically safe usage of objects' protocols

Our language of choice

We will work with a new version of the language

- Aspects where the language was incorrect or too restricting were revised
  - Concurrency
  - Use of *null* as a value
  - Shared usages
  - ...
- Assertions were added
  - Boolean expressions on the state of fields and parameters

The problem we address

Observations

- Specifying objects intended behaviour as state machines is natural, but may be demanding and not easy to get right
- Stating, for each method, the required and ensured state of fields and parameters may be easier
- Assertions are part of Java since 2006

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Question

Can we get behavioural types from code with assertions?

The envisaged contribution

Infer, from O.-O. code with assertions, behavioural (class) types ensuring safe interoperability

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Infer, from O.-O. code with assertions, behavioural (class) types ensuring safe interoperability

A type inference system: given a program

- either fails: the code is *not well-typed* (in the standard sense) or it may produce a run-time error due to calling methods in an *incorrect order*;
- or returns a new version of the code with the classes annotated with behavioural types, ensuring *object interoperability*.

Usage inference process

The process is composed by three stages

1. Typestate generation

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1. Typestate generation
2. Usage generation
3. Object usage state inference

Usage inference process

Input example - *File* class

```
class File {

    int linesInFile; int linesRead;
    boolean closed; boolean lineInBuffer; boolean isEof;

    //@invariant linesRead >= 0 && linesRead <= linesInFile;
    //@initial linesRead == 0 && linesInFile == 5
              && !closed && !lineInBuffer && !isEof;
    void File() { ... }

    ...
}
```

Usage inference process

Input example - *File* class

```
class File {

        ...

        //@requires linesRead < linesInFile && !closed && lineInBuffer
                    && !isEof;
        //@ensures linesRead + 1 <= linesInFile
                    && !closed && !lineInBuffer && !isEof;
        string read() { ... }

        ...
}
```

Usage inference process

Input example - *File* class

```
class File {

        ...

        //@requires linesRead <= linesInFile && !closed && !lineInBuffer
                    && !isEof;
        //@ensures (linesRead == linesInFile -> !lineInBuffer && isEof)
                    && !closed;
        boolean eof() { ... }

        ...
}
```

Usage inference process

Input example - *File* class

```
class File {

        ...

        //@requires linesRead == linesInFile && isEof && !closed;
        //@ensures linesRead == linesInFile && isEof && closed;
        void close() {
                closed = true;
        }
}
```

Stage 1 - Typestate generation

Based on the algorithm presented in

G. D. Caso, V. Braberman, D. Garbervetsky, and S. Uchitel. "Enabledness-based Program Abstractions for Behavior Validation". In: ACM Trans. Softw. Eng. Methodol. 22.3 (July 2013), 25:1–25:46. ISSN: 1049-331X

- Enabledness-preserving automata extraction from source code equipped with assertions
- We modified the algorithm to apply it in code with preconditions and postconditions
- We then use a SMT solver to perform the validity checks

Stage 1 - Typestate generation

Choice-based transitions

- Mool allows transitions to have, at most, two target states, with these being based on choice

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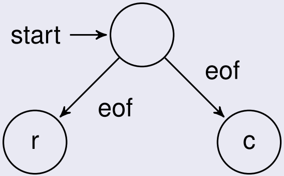
- The algorithm allows nondeterministic transitions with multiple target states



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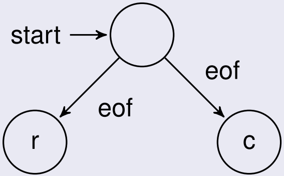

Mool depends on the result of *eof* to know which state to transit to

Stage 1 - Typestate generation

The original algorithm produces the following transition relation

$$\delta(S_a, m) = S_b$$

Meaning that, when executing the method m in state S_a, the object transits to state S_b.

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$$\delta(S_a, m) = S_b$$

Meaning that, when executing the method m in state S_a, the object transits to state S_b.
In a nondeterministic context it is possible to have the following transition relation:

$$(S_a, m, S_{b_1}) \in \delta$$
$$(S_a, m, S_{b_2}) \in \delta$$

Where S_{b_1} and S_{b_2} are different states.

Stage 1 - Typestate generation

In our version the transition relation is *a function*, defined as follows

$$\delta(S_a, m, c) = S_b$$

Where c is the choice the transition corresponds to.

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$$\delta(S_a, m, c) = S_b$$

Where c is the choice the transition corresponds to.
In the previous nondeterministic example, the transition relation could be:

$$\delta(S_a, m, \mathit{false}) = S_{b_1}$$

$$\delta(S_a, m, \mathit{true}) = S_{b_2}$$

Meaning that, if m returns *true* the object transits to state S_{b_2}, otherwise it transits to state S_{b_1}.

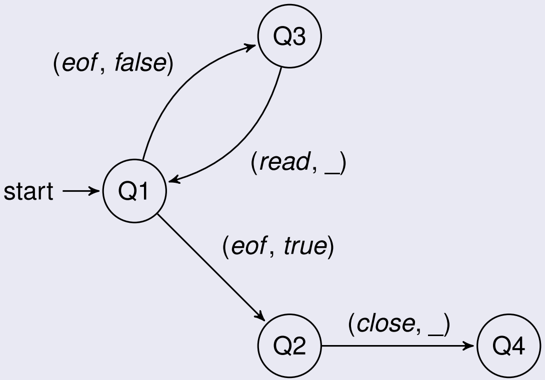
Stage 1 - Typestate generation

Transition relation extension

- To do this, the algorithm needs to know which state corresponds to both true and false branches
- The post-condition must specify the object state in both choices

Stage 1 - Typestate generation

Output example - Typestate of the *File* class



$Q1 = \{eof\}$

$Q3 = \{read\}$

$Q2 = \{close\}$

$Q4 = \{\}$

Stage 2 - Usage generation

Based on the algorithm presented in

P. Collingbourne and P. H. J. Kelly. “Inference of Session Types From Control Flow”. In: Electron. Notes Theor. Comput. Sci. 238.6 (June 2010), pp. 15–40. ISSN: 1571-0661.

- Session type inference for C
- We are only interested in stage three of the algorithm: Graph Simplification and Translation

Stage 2 - Usage generation

Choice-based transitions

- The translation function does not deal with choice-based transitions
- We extend it so that it translates these type of transitions into variant types

$$\begin{array}{l} \delta(S_a, m, \mathit{false}) = (S_{b_1}) \\ \delta(S_a, m, \mathit{true}) = (S_{b_2}) \end{array} \implies S_a = \{m; < S_{b2} \ + \ S_{b1} >\}$$

Stage 2 - Usage generation

Shared state of usage states

- An usage state can be defined as shared or non-shared
- We extend the translation function to infer the shared status of an usage state
- An usage state is considered shared if:
  - Its completely recursive

$$S_a = \{a; S_a + b; S_a\}$$

  - It only transits to equivalent usage states

$$S_a = \{a; S_a + b; S_b\} \qquad S_b = \{a; S_b + b; S_a\}$$

Stage 2 - Usage generation

Output example - Usage of the *File* class

```
usage lin{File; Q1} where
          Q1 = lin{eof; < Q2 + Q3 >}
          Q3 = lin{read; Q1}
          Q2 = lin{close; end};
```

Stage 3 - Object usage state inference

Specifying the initial usage state of fields

- Mool offers the possibility of indicating the state of the usage of a object in its declaration:

```
class FileReader {
        ...
        File[Q3] file;
        ...
}
```

Stage 3 - Object usage state inference

Specifying the usage state of parameters

- Programmers can also define the usage state of parameters:

```
void FileReader(File[Q3] f) {
        file = f;
        ...
}
```

Stage 3 - Object usage state inference

Specifying the usage state of a returned object

- It is also possible to define the usage state of an object returned by a method:

```
File[Q3] getFileToRead() {
        file;
}
```

Stage 3 - Object usage state inference

Usage state declaration in the context of our work

- We do not expect the programmer to know beforehand the states that will compose the generated usage
- But we can expect the programmer to know the state of an object when initialised

Stage 3 - Object usage state inference

Using preconditions to specify the state of an object

- It is possible to express the expected state of the instance received as a parameter in the precondition of the method:

```
class FileReader {
        File file; ...

        //@invariant counter >= 0;
        //@requires f != null && !f.eof();
        //@initial counter == 0 && new File() && !isEof;
        void FileReader(File f) { file = f; ... }
        ...
}
```

Stage 3 - Object usage state inference

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class FileReader {
    File file; ...

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    void FileReader(File[Q3] f) { file = f; ... }
}
```

Stage 3 - Object usage state inference

Using preconditions to specify the state of an object

- It is also possible to know the initial state of an object when it is initialized:

```
class FileReader {
        File[Q3] file; ...

        //@invariant counter >= 0;
        //@requires f != null && !f.eof();
        //@initial counter == 0 && new File() && !isEof;
        void FileReader(File[Q3] f) { file = f; ... }
}
```

Stage 3 - Object usage state inference

Using postconditions to specify the state of a returned object

- This usage state can be inferred using the method postcondition to express the expected state of the returned object:

```
//@requires !isEof;
//@ensures !isEof && !file.eof();
File getFileToRead() {
        file;
}
```

Stage 3 - Object usage state inference

Using postconditions to specify the state of a returned object

- This usage state can be inferred using the method postcondition to express the expected state of the returned object:

```
//@requires !isEof;
//@ensures !isEof && !file.eof();
File[Q3] getFileToRead() {
        file;
}
```

Stage 3 - Object usage state inference

Algorithm steps

1. Determines the usage state of every parameter using the preconditions
2. Analyses the code of the method and:
   - For every initialization, sets the usage state of the initialized variable with the usage state of the value
   - For every call, changes the current usage state of the object the method was called
3. Determines the usage state of the return type using the postconditions

Conclusion

Work summary

- In short, the algorithm does the following:
  - Generates typestates from the code equipped with assertions
  - Translates the typestates into usage types
  - Infers the correct usage state for each declared object

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- In short, the algorithm does the following:
  - Generates typestates from the code equipped with assertions
  - Translates the typestates into usage types
  - Infers the correct usage state for each declared object
- We implemented the algorithm:
  `http://usinfer.sourceforge.net/`

Conclusion

Assertions

- If the assertions are not correct, one of two things might happen:
  - The tool fails to infer the usage types
  - The tool produces usage types that may allow unwanted behaviour
    In that case, typechecking the code with such usage may fail, if it allows erroneous behaviour

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- If the assertions are not correct, one of two things might happen:
  - The tool fails to infer the usage types
  - The tool produces usage types that may allow unwanted behaviour
    In that case, typechecking the code with such usage may fail, if it allows erroneous behaviour
- Thus, the algorithm can also be used to verify the correctness of the assertions

Future work

Correctness

We want to:

- State the intended results
- Prove the algorithm sound

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Correctness

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- State the intended results
- Prove the algorithm sound

Assertions

- Programming with assertions is also hard
- We want to infer them as automatically as possible

Thank you