Modular Transformation of Java Exceptions Modulo Errors

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Outline

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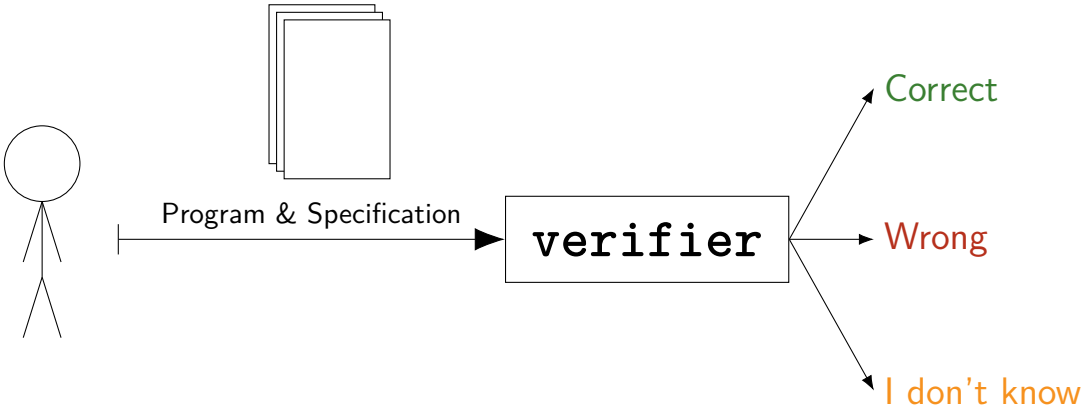
Deductive verification

- Deductive verification ensures a system follows a specification
- Correct w.r.t. a deductive system of rules
- User only reads & writes specification

Deductive verification: workflow



Deductive verification in practice

```
1  //@ ensures (a > b ? a : b) == \result;
2  //@ signals (ArithmeticException e) a < 0 || b < 0;
3  int max(int a, int b) {
4    if (a < 0 || b < 0) {
5      throw new ArithmeticException();
6    }
7    return a > b ? a : b;
8  }
```

Listing 1: An implementation of a method computing the maximum of two integers.

VerCors

- Deductive verifier for concurrent languages
- Separation logic
- Data races & functional correctness

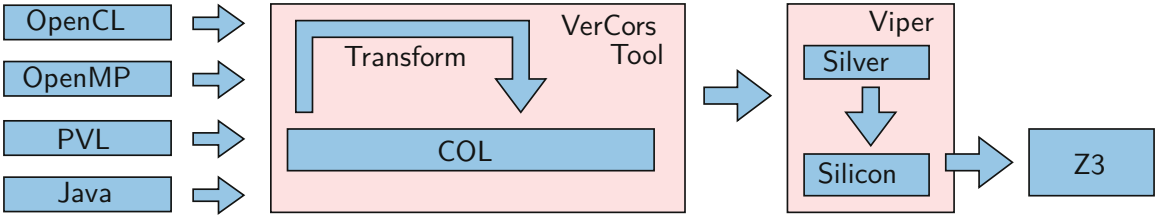


Figure 1: Architecture of VerCors

Verifier usage in practice?

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Possible answers:

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Deductive verifier capabilities

Name	Language	Separation logic	Exceptions
Nagini	Python	✓ Yes	✓ Yes
Gillian-JS	JavaScript	✓ Yes	✓ Yes
Verifast	Java	✓ Yes	✗ Up to `finally`
jStar	Java	✓ Yes	✗ Trivial `finally`
KeY	Java	✗ No	✓ Yes
OpenJML	Java	✗ No	✓ Yes
Krakatoa	Java	✗ No	✗ Up to `finally`

Table 1: Deductive verifiers and their capabilities

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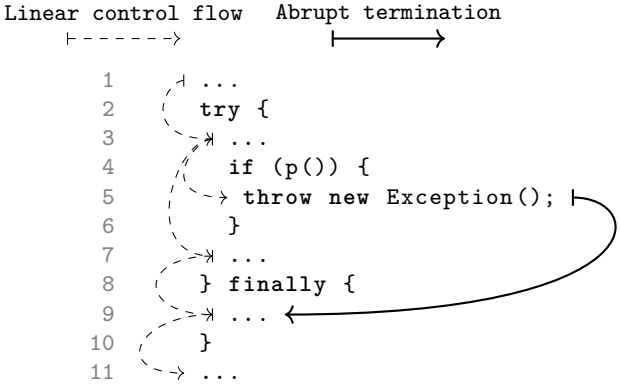
Table 1: Deductive verifiers and their capabilities

Abrupt termination

- Abrupt termination: statement terminates earlier that normally expected
- Control flow redirected to any program point $\implies$ not linear/structured
- Examples:
  - `throw`
  - `return`, `break`, `continue`
  - Labeled `break`, `continue`

Abrupt termination: `throw` & `finally`



Listing 2: Example usage of `throw` and `finally`

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Error types:

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Errors and error sources are not one-to-one!

Annotation overhead: out of memory error source

```
1  String concatenateWithSemicolon(String a, String b) {
2    StringBuilder sb = new StringBuilder();
3
4    sb.append(a +   ";");
5    sb.append(b +   ";");
6
7    return sb.toString();
8  }
```

Listing 3: A method which concatenates two strings

Annotation overhead: out of memory error source

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1  String concatenateWithSemicolon(String a, String b) {
2    StringBuilder sb = new StringBuilder();①
3
4    sb.append(a +② ";");③
5    sb.append(b +   ";");
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7    return sb.toString();④
8  }
```

Listing 3: A method which concatenates two strings

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The “ideal” semantics

- Ideal static analysis tool: implements Java Language Specification (JLS)
- Maximizes chance of capturing bug behaviour

Why the ideal semantics is less useful

1. Induced annotation overhead in user code
2. Run-time dependency

Annotation overhead: implications

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Most Java methods will need the following contract in the ideal semantics:

```
//@ signals (OutOfMemoryError) true;
```

Annotation overhead: implications

Note: problem is not implementing all error sources in VerCors/verifier, but meaningless annotations that user will have to write!

Run-time dependency

- Error sources may depend on the runtime environment:
  - `ClassFormatError`: loading improperly formatted code
  - `InternalError`: JVM bug occurs
- Avoid flooding user with unworkable run-time requirements
  - Classpath, VM version, ...
  - **Non-standard**

Why the ideal semantics is less useful: conclusion

1. Induced annotation overhead in user code
2. Run-time dependency

$\Longrightarrow$ The ideal semantics is not useful if implemented

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An optimal and usable semantics

Definition (Exceptions modulo errors)

A subset of Java semantics where exceptions can only come from the `throw` statement and method calls.

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A subset of Java semantics where exceptions can only come from the `throw` statement and method calls.

Definition (VerCors exception guarantee)

All thrown exceptions are either:

- Handled in a catch
- Indicated in a throws clause

Additionally, the following errors will not occur:

- `NullPointerException` when a `null` reference is dereferenced.
- `ArithmeticException` when division by zero or modulo zero takes place.
- `ArrayIndexOutOfBoundsException` for out of bounds array accesses.

An optimal and usable semantics: motivation

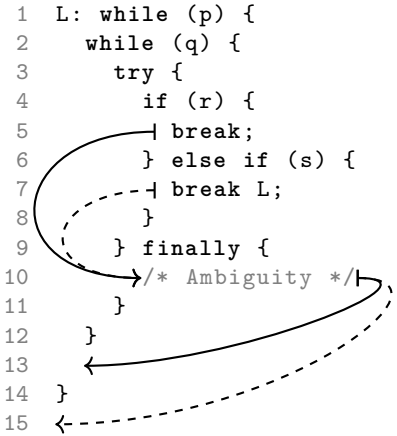
- Reduces annotation burden
  - No annotations for `InternalError`, `OutOfMemoryError`, ...
- In practice, `throw` and `throws` are the only considered sources.
- Users can "opt in" to certain error sources by adding `throws`/`signals` manually to user code.

Outline

Encoding exceptions without `finally`: ok

- `break` exits a `while`
- `continue` jumps back to beginning
- `return` exits method
- `throw` jumps to `catch`

Encoding exceptions with `finally`: ambiguity



Listing 4: `finally` can introduce ambiguous code paths

Three implementation strategies

- Inlining: intuitive, but risks blowup
- Control flow flags: avoids blowup, harder to implement
- Via exceptions

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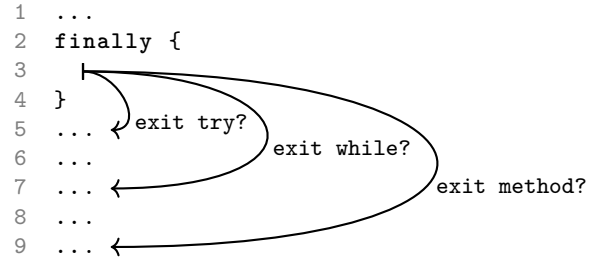
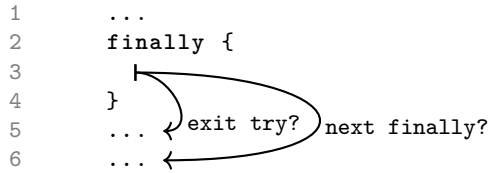
What to do after a finally?



Listing 5: Where to go after a `finally`?

What to do after a finally, simplified



Listing 6: Two paths remain when considering only exceptions

Implementation strategy: via exceptions

- Insight: for exceptions, `finally` is straightforward
- Strategy:
  1. Abrupt termination to exceptions
  2. Exceptions to `goto`
- Transformation becomes more modular
- `break`/`return`/`continue` $\implies$ `throw` is straightforward

Transforming `break` into `throw`

```
1 l: while (p) {
2   ...
3   break l;
4   ...
5 }
```

Listing 7: Before transformation

```
1 try {
2   while (p) {
3     ...
4     throw new BreakLException();
5     ...
6   }
7 } catch (BreakLException e) { }
```

Listing 8: After transformation

Outline

Evaluating exceptions modulo errors

How to evaluate exceptions modulo errors?

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How to evaluate exceptions modulo errors?

1. What are common exception patterns from commercial software?
2. Can VerCors verify the patterns?

Evaluation table

Used in `catch`	**Used in `finally`**
Empty	Empty
Log, stack trace	Log
`if`, `while`, `switch`, `continue`, `break`, `return`	`continue`, `return`
`throw e`, `throw new E()`, `throw new E(e)`	`throw new E()`
Nested `try`	Nested `try`

Table 2: Exception pattern overview.

Example program

```
1  class CatchStackTrace {
2      void m () {
3          try {
4              throw new Exception();
5          } catch (Exception e) {
6              e.printStackTrace();
7          } } }
```

Listing 9: Example program `CatchStackTrace.java`.

Discussion

- Exceptions modulo errors *might* miss bugs
  - Failing allocations, stack overflow, ...
  - **Beneficial tradeoff**
- Backend requirements
  - `goto`
  - Conditional permissions
    - `ensures b ==> Perm(x, write);`
    - *`RuntimeException is thrown`* `==> Perm(x, write);`
- Performance
  - Bigger encoded output, complex control flow, more conditional permissions
  - Inherent to exceptions
  - Not problematic in practice

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Conclusion

- An approach for supporting exceptions in a deductive verifier
  - First convert control flow into exceptions
  - Then convert exceptions into `goto`
- A simplified exception semantics, "exceptions modulo errors"
  - Reduces annotation burden for the user
  - At the cost of less precision
- Evaluated exceptions modulo errors against common exception patterns
  - It can handle common exception patterns