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Corrective Hints for Type Incorrect Generic Java Programs

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- How can we modify the type checking process of Java, so that implementations may give more informative error messages?

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- How can we modify the type checking process of Java, so that implementations may give more informative error messages?
  - Zooming in: only for generic method invocations
    A first step was published in (Boustani et al, PEPM '09)
    - Zooming in: providing hints that may help resolve type errors.

In a larger context

- My agenda: Error Diagnosis Oriented Static Analysis
- Multiple languages, multiple paradigms, multiple analyses.
  - Java, Haskell, PHP, JavaScript
  - intrinsic type systems, security analysis, optimizing analyses with explicit annotations.
- Cross-fertilization: parametric polymorphism in Haskell prepares for genericity in Java.
- Sharing experience, heuristics and implementations between compilers
- Back to Java...

A selection of complications

- The (generics part of the) JLS is large and complicated
- The JLS is operational rather than declarative.
  - Hard on programmers, harder on compiler builders.
- Type error messages provided by major tools are not very informative
- Types not part of the program are constructed and appear in error messages
- Compilers follow the JLS slovenly
  - Similar issues, but dissimilar messages
  - Deviation from JLS gives programs that should not compile
- See (Boustani et al, PEPM '09) for illustrations.

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Danger: we may easily guess wrong.

A solution: weigh evidence in order to decide when to provide hints.

Implemented into Jastad EJC (Hedin et al.)

1. Examples

Example 1: exploit return type invariance


```
<T> List<T> foo(Map<T, ? super T> a){}
...
Map<Number, Integer> m = null;
List<Integer> ret = foo(m);
```

javac:

```
cxt_heuristic/Test1.java:6:
<T>foo(Map<T,? super T>) in Test1 cannot be applied
to (Map<Number,Integer>)
```

ejc:

```
The method foo(Map<T, ? super T) in the type Test1
is not applicable for the arguments
(Map<Number,Integer>)
```

Example 1: exploit return type invariance


```
<T> List<T> foo(Map<T, ? super T> a){}
...
Map<Number, Integer> m = null;
List<Integer> ret = foo(m);
```

ours:

```
cxt_heuristic/Test1.java:6
Method <T>foo(Map<T, ? super T>) of type
Test1 is not applicable for the argument of
type (Map<Number, Integer>), because:
  [*] The type Integer in Map<Number, Integer>
  on 5:9(5:21) is not a supertype of the inferred
  type for T: Number. However, replacing Number
  on 5:13 with Integer may solve the type conflict.
```

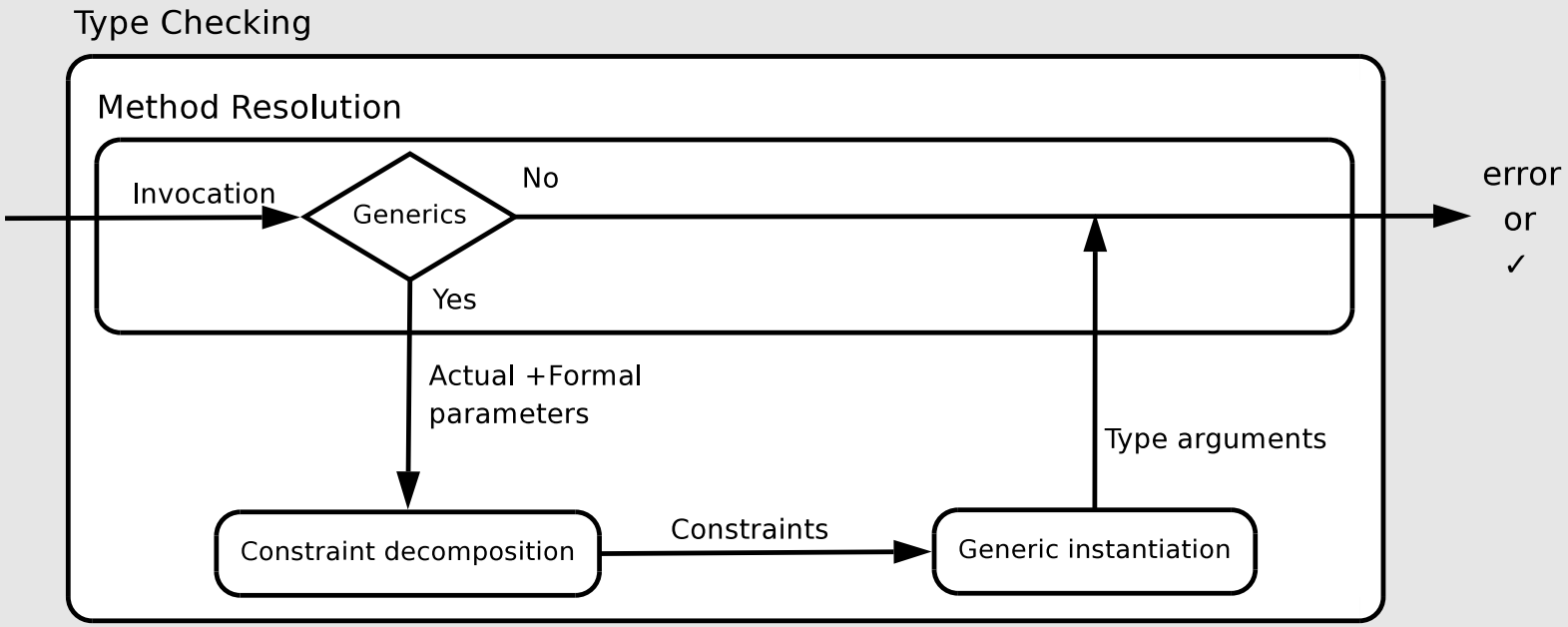
Example 2: satisfy subtype conflicts


```
<T> void foo(T a, T b,
             Map<? super T, ? super T> c) {}
...
Map<Number, Double> m = ...;
Number n = ...;
foo(1, n, m);
```

```
Test1.java:13
Method <T>foo(T, T, Map<? super T, ? super T>) of
type Test1 is not applicable to the arguments of
type(int, Number, Map<Number, Double>), because:
  [*] The type Double in Map<Number, Double> on
  11:9(11:21) is not a supertype of the inferred
  type for T: Number. However, replacing Double on
  11:21 with Number may solve the type conflict.
```

2. Adapting the type checking process

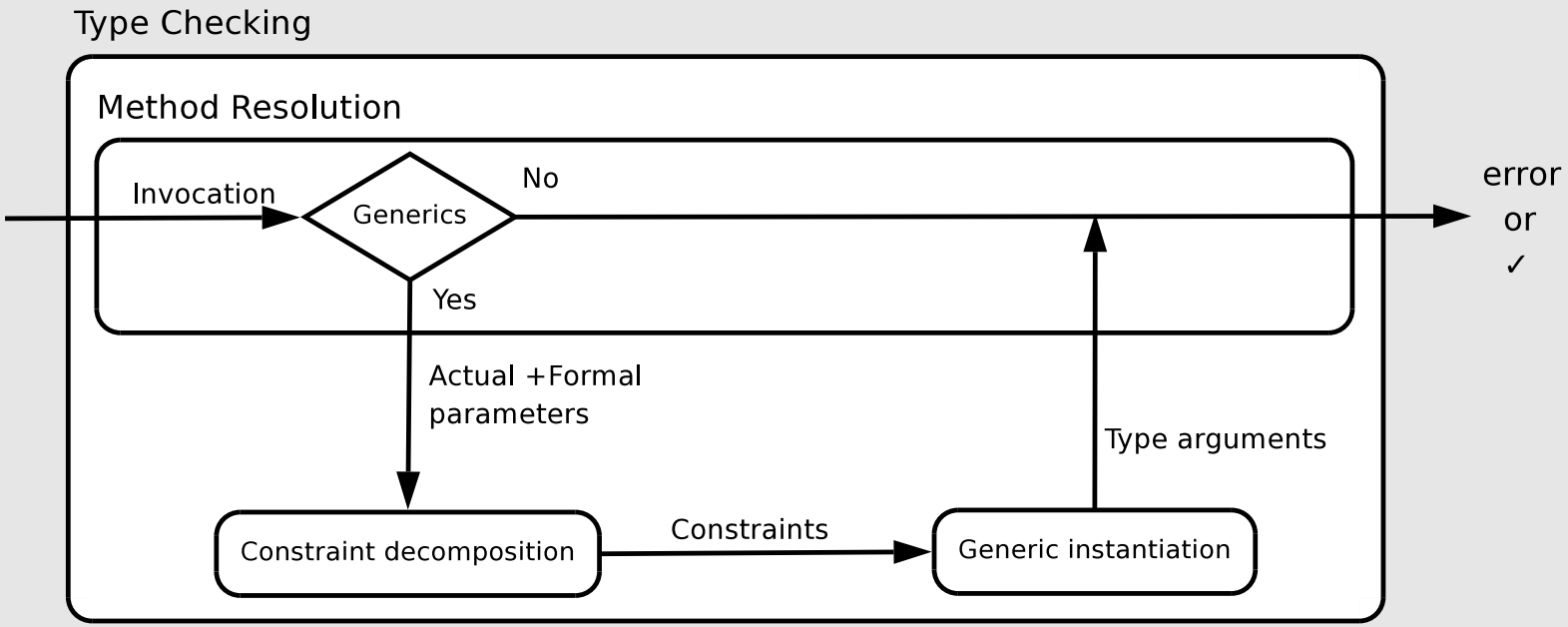
The Java type checking process



Method resolution determines a single, most specific method that the programmer may be calling.

- Multiset is reduced by applying various heuristics.
- Ambiguity, or lack of a fitting method: error message is returned.

The Java type checking process



Relate arguments to parameters via constraints:

`foo(new HashMap<Number, String>, new Integer(2))`

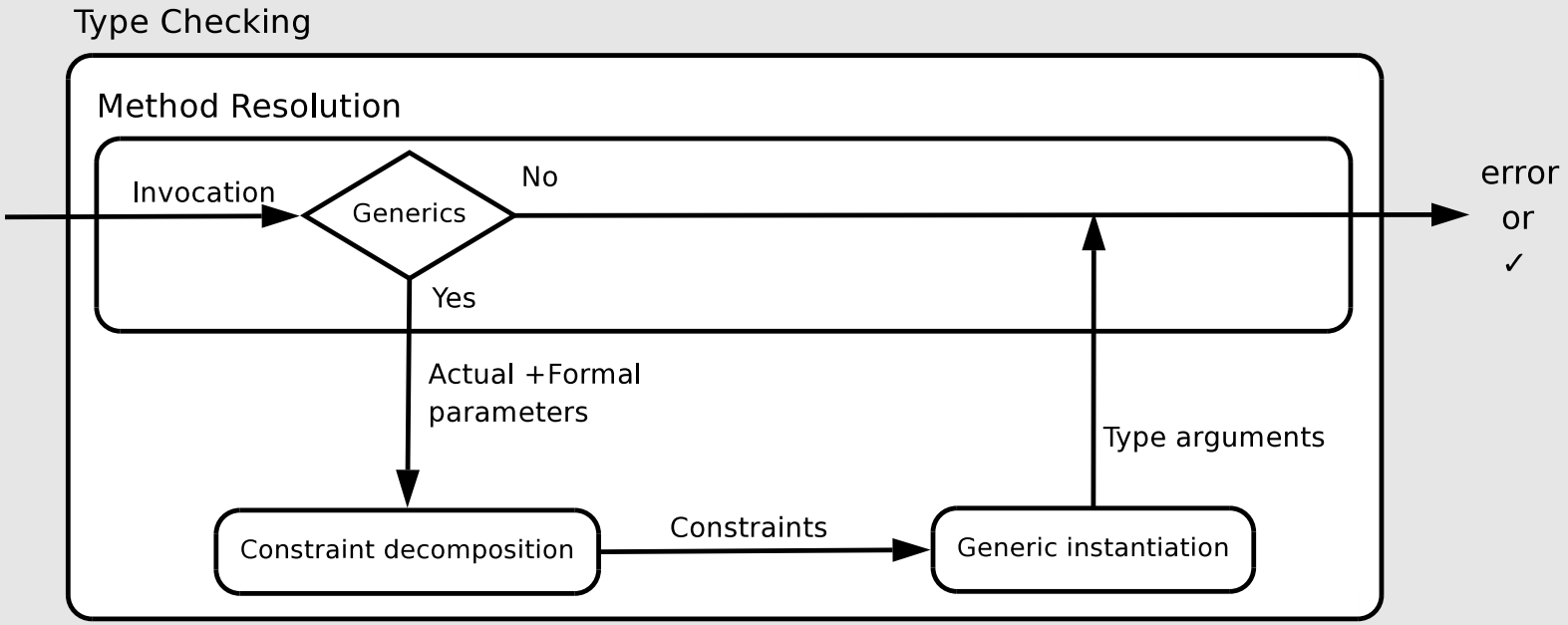
to call `void foo(HashMap<T,S extends T> map, S)`

gives

`HashMap<Number, String>` $<:$ `HashMap<T, S extends T>`

`Integer` $<:$ `S`

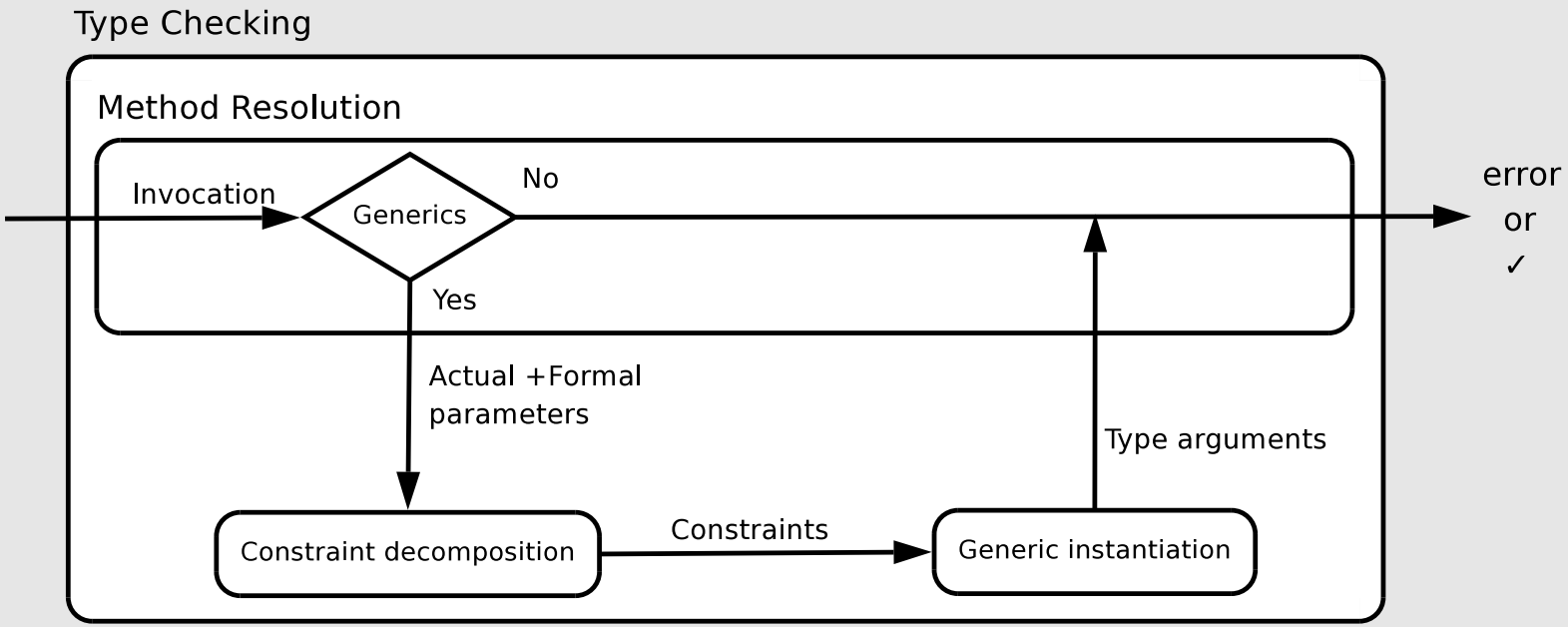
The Java type checking process



Decompose constraints: we get

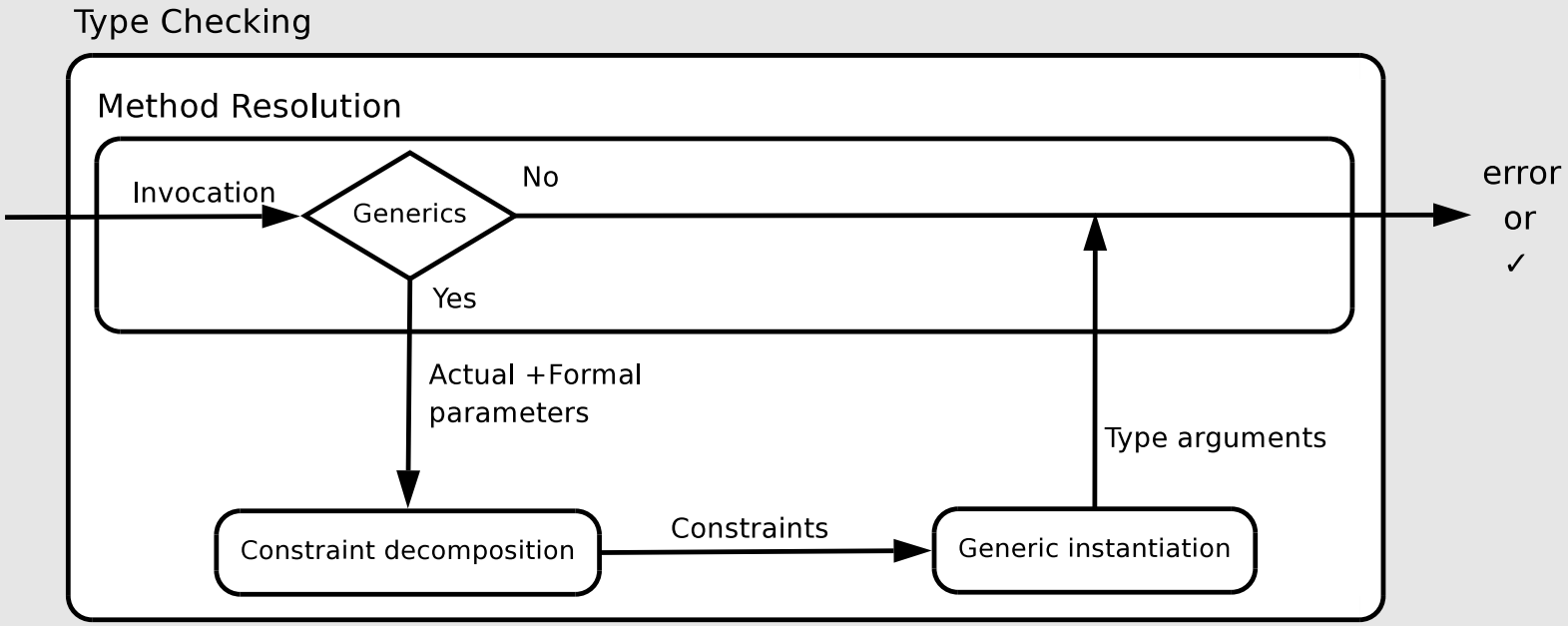
$$\{\mathtt{T} = \mathtt{Number}, \mathtt{S} = \mathtt{String}, \mathtt{S} <: \mathtt{T}, \mathtt{Integer} <: \mathtt{S}\}$$

The Java type checking process



Type inference/generic instantiation:
find "suitable" types for `T` and `S`, `T` = `Number` and `S` = `String`.

The Java type checking process



Type inference/generic instantiation:
find "suitable" types for `T` and `S`, `T` = `Number` and `S` = `String`.
Type checking:
subtype constraint `S` <: `T` and `Integer` <: `S` both fail.

Adaptations to the Java type checking process §2

- Principle 1: relax
  - Allow more than one candidate method.
  - Avoid taking decisions influenced by what is likely to be wrong. Erase generics!
- Principle 2: don't change, add
  - Error messages are constructed after type checking has failed.
- Principle 3: hold on (to constraints)
  - Message is based on the original constraints.
- Again, see (Boustani et al, PEPM '09)

Conflict of interest?

- deciding type correctness is easier with simplified constraints, but
- the original constraints are closer to the program.
  - easier to make informed decisions
  - error messages will make more sense
  - makes it possible to provide hints

Conflict of interest?

- deciding type correctness is easier with simplified constraints, but
- the original constraints are closer to the program.
  - easier to make informed decisions
  - error messages will make more sense
  - makes it possible to provide hints
- In practice, compiler builders choose one of the two approaches
- But why not do both?

How does it work, a stepwise description

- After a type error is discovered, we consider the original constraints anew.
- The constraints cannot be satisfied simultaneously.
- But which constraint(s) are most likely to be responsible?
- Based on that information we can
  - provide a suitable error message
  - try to come up with a hint that solves the problem.
- Various heuristics consider the set of constraints (independently) and try to find a suitable hint.
- An error manager decides which of these is best
  - Heuristics are currently ranked in a fixed order.
- and attaches it to the error message.

3. Heuristics

Heuristics

We add heuristics to the process to:

- Bias the error messages in the presence of enough evidence.
  - Ten say `T` should be `Number`, one says its `String`.
- Encapsulate expert knowledge about the kind of mistakes people make.
  - Not every programmer understands that or why collector classes are invariant, so if that knowledge solves the problem we can explicitly mention this.
- Heuristics decide which constraint is erroneous, but also suggest how to avoid generating that constraint in the next compile.
  - Suggest to replace `String` with `Number`.

In more detail: context type invariance and super Object

Example: exploit context type invariance (again) §3

```
<T> List<T> foo(Map<T, ? super T> a){}
...
Map<Number, Integer> m = null;
List<Integer> ret = foo(m);
```

Works under the following circumstances

- method has a generic/parameterized return type
- that contains type variables
- method invocation is in an assignment context
- the assignment should give rise to an equality constraint
  - Here between `T` and `Integer`

Example heuristic: context type invariance §3

```
<T> List<T> foo(Map<T, ? super T> a){}
...
Map<Number, Integer> m = null;
List<Integer> ret = foo(m);
```

- The assignment gives concrete information about `T`.
- that we hope is correct.
- Verify that information is consistent with constraints derived from the method signature.
- What should change in the invocation to accommodate: `Map<Number, Integer>` $\Longrightarrow$ `Map<Integer, Integer>`
- The hint suggests this change: `However, replacing Number on 5:13 with Integer may solve the type conflict.`

Example: context type invariance (advanced) §3

```
<T, R, S extends Map<R, T>>
    Map<T, R> baz(T a, R b, S c) {}
Number t = ...;
Number r = ...;
Map<Double, Integer> ms = ...;
Map<Integer, Double> ret = baz(t, r, ms);
```

```
<omitted for reasons of space> because:
  [*] The type Map<Double, Integer> on 14:9 is
  not a subtype of S's upper bound Map<Number,
  Number> in 'S extends Map<R, T>'. However,
  replacing the types:
  - Number on 12:9 with Integer
  - Number on 13:9 with Double
  may solve the type conflict.
```

Example heuristic: super Object

- What can you do with a variable of the following type?

  `List<? super Object>`

- Any value can be added to the list: every type is a subtype of `Object`, so also of any supertype of `Object`.
- You can only safely read values of type `Object`.
- Therefore, the list behaves exactly like `List<Object>`.
- The use of `?` may make a program type incorrect.
- The heuristic
  - detects constraints that mention `? super Object`
  - replaces these parts with `Object`,
  - verifies that the constraint set becomes satisfiable.
- Similarly, `? extends X` where `X` is final can be dealt with.

Example: super Object


```
<T> void foo(Map<T, T> a) {}
...
Map<? super Object, ? super Object> m = ...;
foo(m);
```

```
Test1.java:6
Method <T>foo(Map<T, T>) of type Test1 is not
applicable to the argument of type
(Map<? super Object, ? super Object>), because:
  [*] '? super Object' may not always equal
  '? super Object' and invariance demands this.
  However, replacing
  - '? super Object' on 5:13
  - '? super Object' on 5:28
  with Object may solve the type conflict.
```

4. Wrapping up

Summary

- I have
  - sketched the type inference process,
  - discussed the use of heuristics,
  - illustrated by one or two example heuristics,
  - and gave examples of their effects.
- I omitted
  - majority heuristic for equality constraints (5.1)
  - confusing `super` and `extends` (5.3).
  - mismatches between `super` and `extends` (5.3.2)
  - majority heuristic for subtype conflicts (5.4)
  - warnings (5.5)
  - illustrated by many more examples
  - related work

Future work

- Become a (Generic) Java expert
- Thus far only (generic) invocations.
  - What about other constructs, like inner classes?
- More heuristics, also for the non-generic parts
- Expert and experimental validation.
- Collect programs: weird and normal.
  - Have any? Send them to jur@cs.uu.nl.
- Other combinations of subtyping and generics.
  - Johan Nordlander's Timber