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Design by Contract for Java - Revised

Master's thesis - Johannes Rieken

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Outline

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- Introduction: Design by Contract (DBC)
- Existing approaches:
  - *"How to specify / validate / enforce contracts?"*
  - Summary of existing approaches
- A *new* approach to implement DBC for Java
  - Fundamentals: *Java 5 Annotations, Annotation Processing API, Java Compiler API, Instrumentation API*
  - *"How to specify / validate / enforce contracts? - Revised"*
  - Demo
  - Summary

Design by Contract (DBC)

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- Brainchild of Bertand Meyer, firstly implemented in *Eiffel*
- Basic idea: Improve software reliability by defining contracts between interacting software components
- When invoking a method, contracts state which **pre-conditions** a client must fulfil, and what **post-conditions** a supplier guarantees
- Further concepts: Invariants, Side-effect freeness, Pre & Post-state, Inheritance of contracts

```
public double sqrt(int n){
 pre n >= 0;
 ...
 post (\result * \result) == n;
}
```

DBC in Java

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- Java does not support DBC - except for the "simple assertion facility"
- Allows to define assertions with the assert keyword
- Full support for DBC remains the most requested enhancement
- Numerous tools and extensions exist:
  - Java Modelling Language (JML), Iowa State University
  - Jass (Java with Assertions), Universität Oldenburg
  - jContractor, Contract4J, C4J, OVal, AOP
  - ...
- Still, DBC can only rarely be seen in the Java World

DBC-Approaches: *Requirements*

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- Functional Requirements:
  - How to specify contracts?
  - How to validate contracts?
  - How to enforce contracts?

- Non-functional Requirements:
  - Ease-of-use (Specify and validate contracts easily)
  - Seamless integration into IDEs and build processes

How to specify contracts? *(1/2)*

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- Any kind of Java comment

```
/**
 * @pre o != null */
public void add(Object o) { ... }
```

```
public Object get(int i) {
  /** i >= 0 **/
  ...
}
```

```
/*@ ensures \result != null @*/
public Object last() { ... }
```

- Java Method, AOP-Aspect

```
pointcut contractTarget() : call(void Buffer.add(Object));
before() : contractTarget() {
 assert thisJoinPoint.getArgs()[0] != null;
}
```

```
boolean last_PostCondition(Object _Result){
   return _Result != null;
}
```

- Java 5 Annotations

```
public void add(@NotNull Object o) { ... }
```

```
@Contract( bind = BufferContract.class)
public Object get(int i) { ... }
```

```
@Post(expr = "@Result != null")
ublic Object last() { ... }
```

How to specify contracts? *(2/2)*

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	Java Comments	AOP-Aspects / Java Methods	Java 5 Annotations
Possible targets	everywhere	targets methods	types, fields, methods, parameters, packages
Bytecode representation	no, pre-processor or compiler is obligated	yes, but without target	yes
Processing tools	Doctlet API (limits targets)	AOP-Tools, Java compiler	Annotation Processing Tools
Notes	Requires parsing as Java comments are Strings only, no tool support!	a "contract method" or aspect must be assigned to the right method	Possibly used as a "String-container" which requires further parsing

Validate & enforce contracts

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- Once a contract has been specified, it
  - should be validated like any other Java expression (optional, but desired)
  - must be enforced at runtime
- Different technical approaches exists:
  - Pre-Processor
  - Bytecode Instrumentation
  - Custom Compiler
  - Aspect Oriented Programming
  - Interpreter

Pre-Processor

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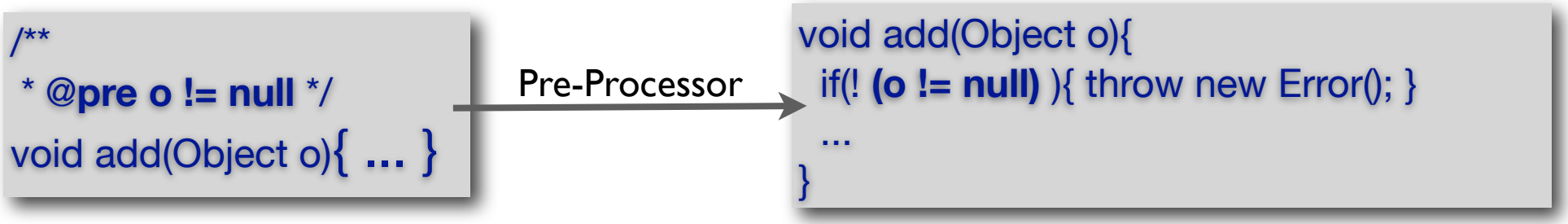

- Performs sourcecode to sourcecode transformation
- Involves (a) a parser for the actual programming language and (b) a parser for the assertions, (c) source-code rewriter

✓ Easy to understand and straightforward to implement

- High maintenance costs as Java evolves, writing a good parser it not trivial
- Tool chain which is hard to integrate, e.g. Eclipse, NetBeans
- Errors puzzle users, because the executed code differs from the written code

Bytecode Instrumentation

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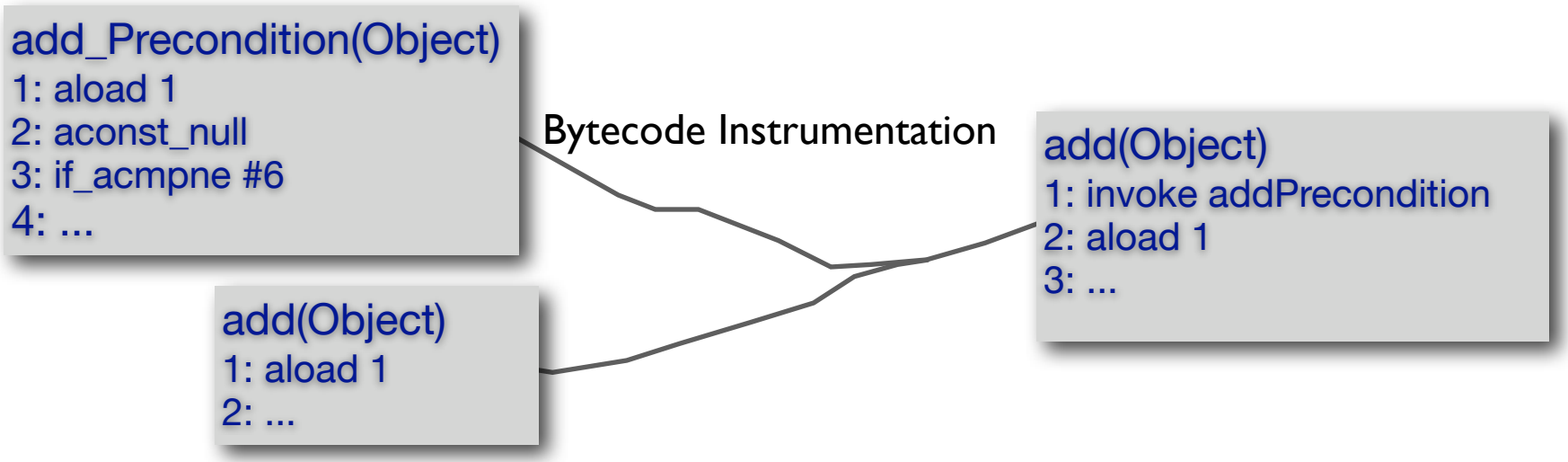

- "Weave" contract method into target method (bytecode 2 bytecode transformation)

✓ Bytecode transformation can be performed transparently

- Where does the bytecode for contracts come from?

- Dynamic bytecode instrumentation is slow - esp. when bytecode is generated on-the-fly

- Static bytecode instrumentation requires an addition processing step

Validate & Enforce contracts:

Custom Compiler

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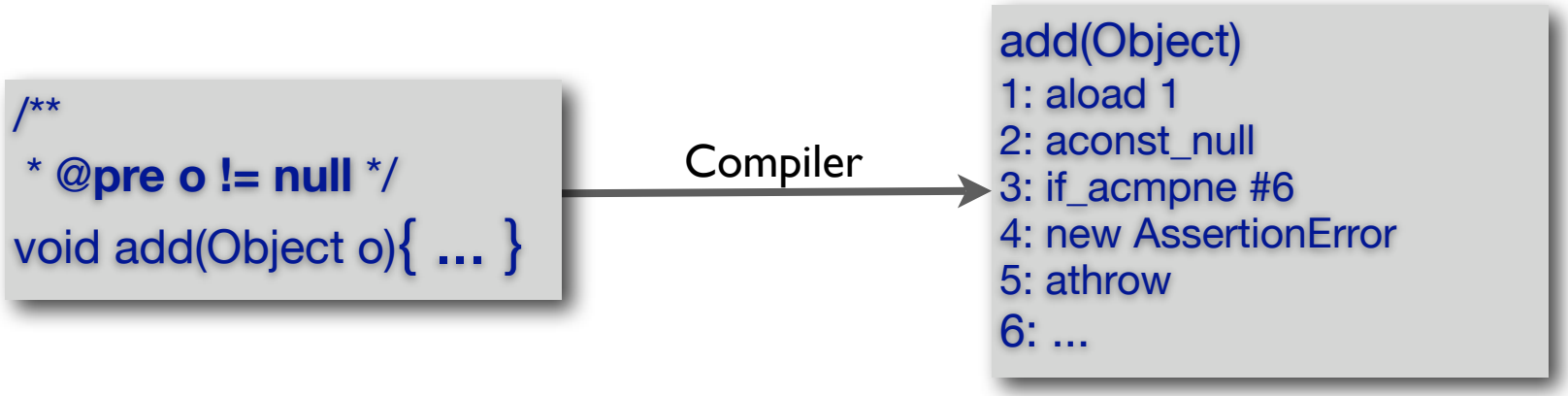

- Sourcecode to bytecode transformation
- Involves (a) a parser for the actual programming language and (b) a parser for the assertion, and a bytecode generator

✓ Most natural way to integrate DBC into Java

✓ No tool chain or alike

- Extremely high engineering and maintenance costs
- Users tend to stick to the default compiler

AOP & Interpreter

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1. Aspect Oriented Programming (AOP) to weave contracts into code
   - contracts is either specified as aspect, or
   - aspect is generated by a pre-processor from a contract
   - ✓ DBC is a cross-cutting-concern
   - \- AOP is not Java!
2. Interpreter Approach evaluates contracts on-the-fly
   - ✓ Requires no pre-processing (e.g. compiler, bytecode instrumentation), but uses a evaluation engine like JRuby or Groovy
   - \- Evaluation errors because of invalid contracts
   - \- Some evaluation engines differ slightly from Java syntax

Summary: *Existing Approaches*

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- Approaches, introduced so far, have drawbacks
  - High engineering or maintenance costs (pre-processor, compiler)
  - Hard to integrate into IDEs or build processes (pre-processor)
  - Different programming paradigms (AOP)
  - Lack of ease of use (Comment-based tools, Interpreter)

✓ Solution: Utilise enhancements that came with Java 5 and Java 6

- Java 5 Annotations, Annotation Processing API (JSR 269)
- Compiler API (JSR 199)
- Instrumentation API

Basics: *Java 5 Annotations*

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- An annotation is a "type-safe comment" build for automatic processing
- Annotations are types, similar to Java interfaces but more restricted

```
@interface Todo {
 String subject();
 float duration() default 1;
}
```

Definition

```
@Todo(
   subject = "Implement method!",
   duration = 2.6 )
public void foo(Object bar){ }
```

Application

  - may define attributes which store compile-time constants
  - data type of attributes must be a primitive, a string, java.lang.Class, an enum-type, other annotations, or an array of these types
  - the meta-annotation java.lang.annotation.Target allows to restrict possible targets (e.g. methods only)

Basics: *Annotation Processing API*

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- Evolved from JSR 269 and added in Java 6 (forerunner is the annotation processing tool from Java 5)
- Allows to write plug-ins for the Java compiler
- Allows to issue error and warning messages
- Provides a model to access the program currently being compiled
- Easy to integrate: Every annotation processor, that can be found on the classpath, participates in the compilation process by default
- Tools supporting JSR 269: Javac, NetBeans, Idea, and Eclipse (3.3)

Basics: *Compiler & Instrumentation API*

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- *Compiler API* evolved from JSR 199 and was added in Java 6
- Allows to interact with the Java compiler on a high level
- Source & Bytecode files are represented as file objects which enables arbitrary implementations, esp. in-memory source files
- Reporting-Infrastructure for error and warning messages

- *Instrumentation API* leverages support for bytecode instrumentation
- A Java-agent is loaded by the JVM prior to a program, and
- can instrument bytecode while the program is loaded into the JVM
- Easy to integrate: Use the -javaagent switch of the java program

Novel Approach

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- Functional Requirements:
  - How to specify contracts? - *Java 5 Annotations*
  - How to validate contracts? - *Annotation Processing & Compiler API*
  - How to enforce contracts? - *Bytecode Instrumentation & Compiler API*

- Non-functional Requirements:
  - Ease of use (Specify and validate contracts easily) - *Standard Java*
  - Seamless integration into IDEs and build processes - *Standard Java*

Specification Annotations

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- @Invariant
- @Model, @Represents

```
abstract class Foo {
 @Invariant("bar != null") Object bar;
}
```

- @Pre, Post
- @SpecCase, @Also

```
@Also({
 @SpecCase( pre = "o != null", post = "contains(o)" ),
 @SpecCase( pre = "o == null", signals = NPE.class) })
void add(Object o){ ... }
```

- @Pure

```
void openValve(@Range(from = 0, to = 100) int n) { ... }
```

```
@NonNull Object get(){ ... };
```

- @NonNull, @Min, @Max, @Range, @Length
- *Specification Expressions*, not annotations: @Result, @Signal, @Old, @ForAll, @Exists

```
@Post("@Old(size) + 1 == size")
public void add(Object o) { ... }
```

Validate Contracts *(compile-time)*

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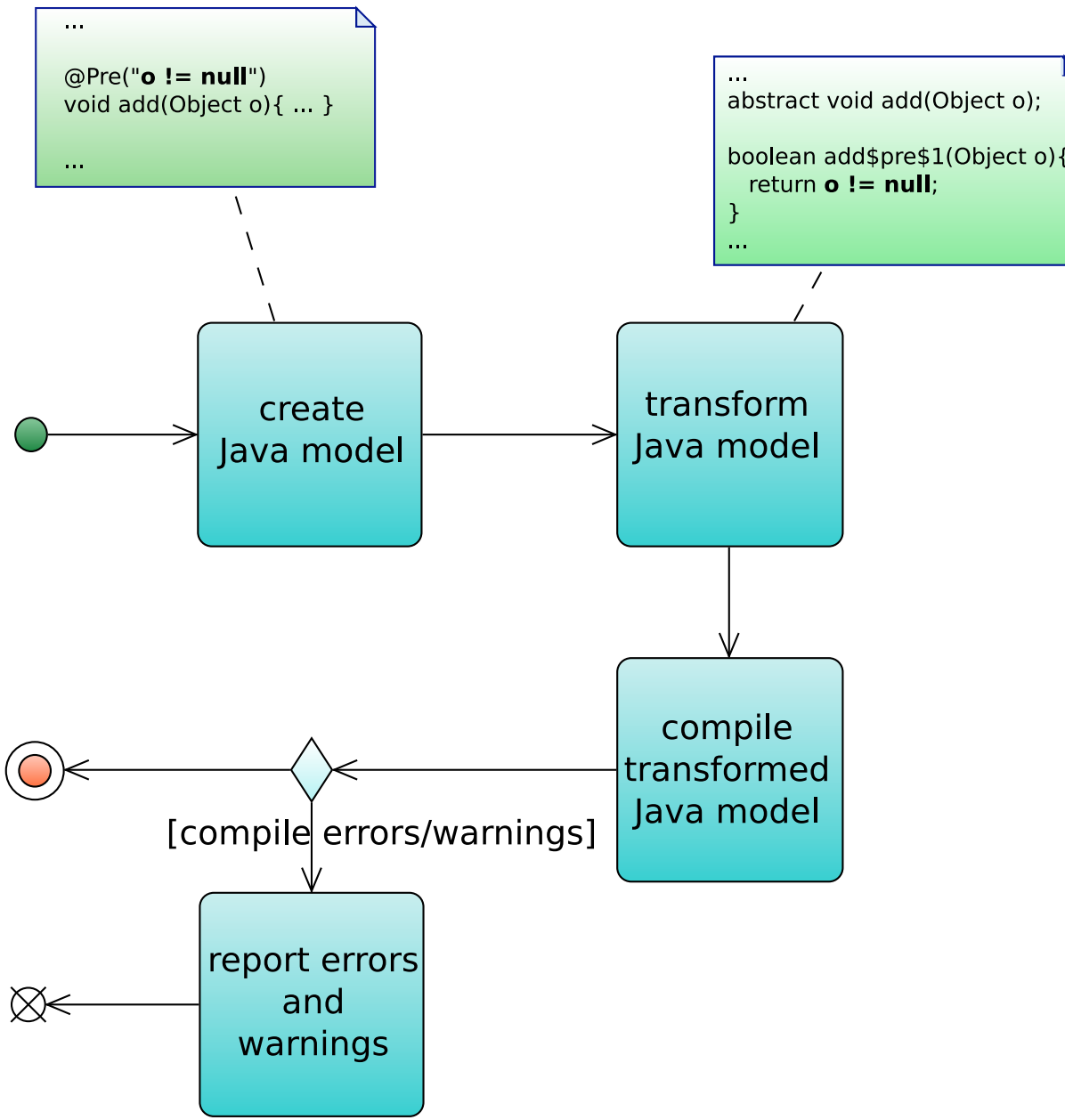

1. Be an annotation processor & have a model reflecting the structure of the program
2. Create contract methods - the body of a contract method is the content of an annotation
3. Compile the transformed model
4. Link errors and warnings in contract methods with the corresponding annotation
5. Annotation Processing API to report messages

Validate Contracts *(compile-time)*

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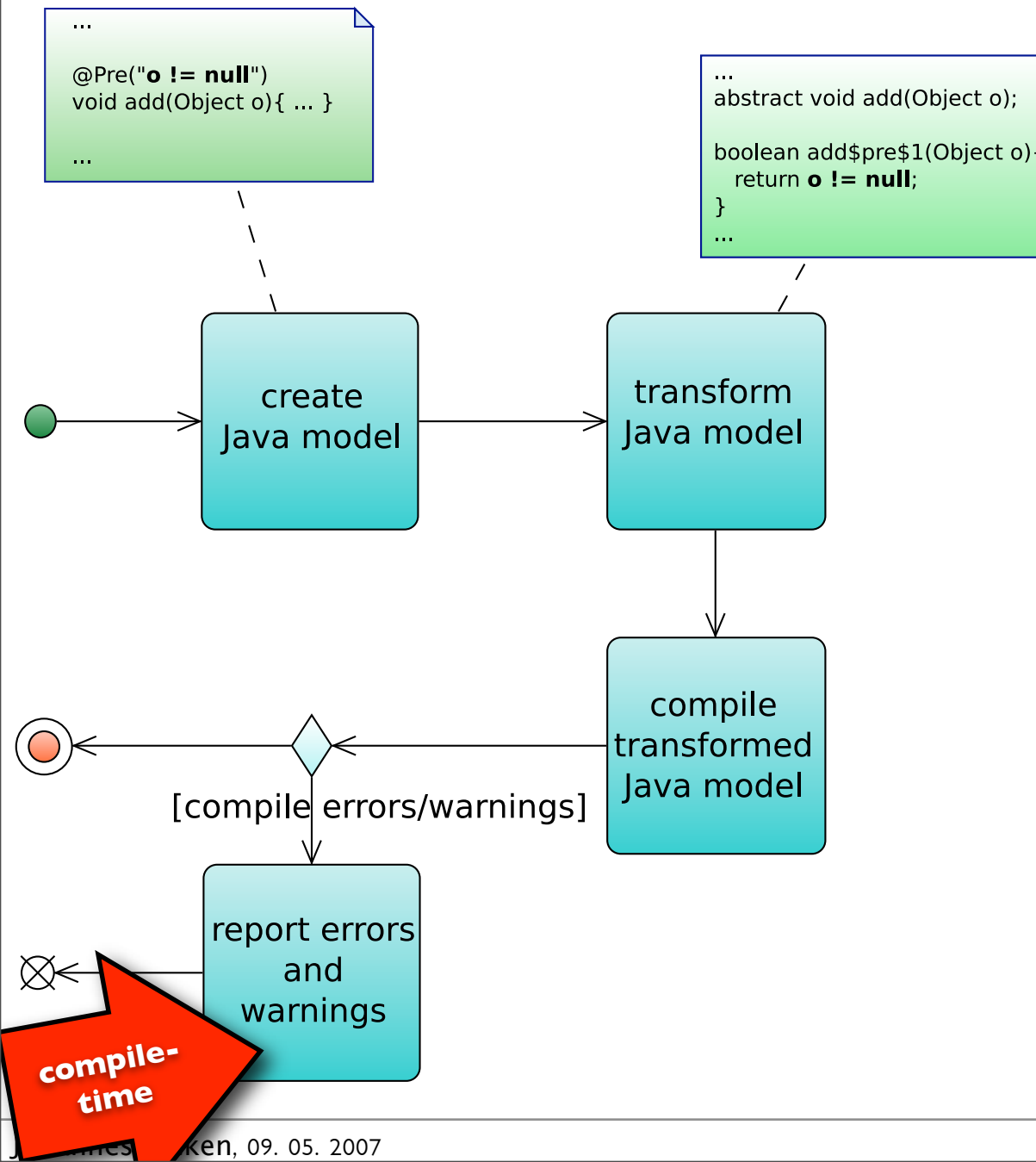

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Enforce Contracts *(runtime)*

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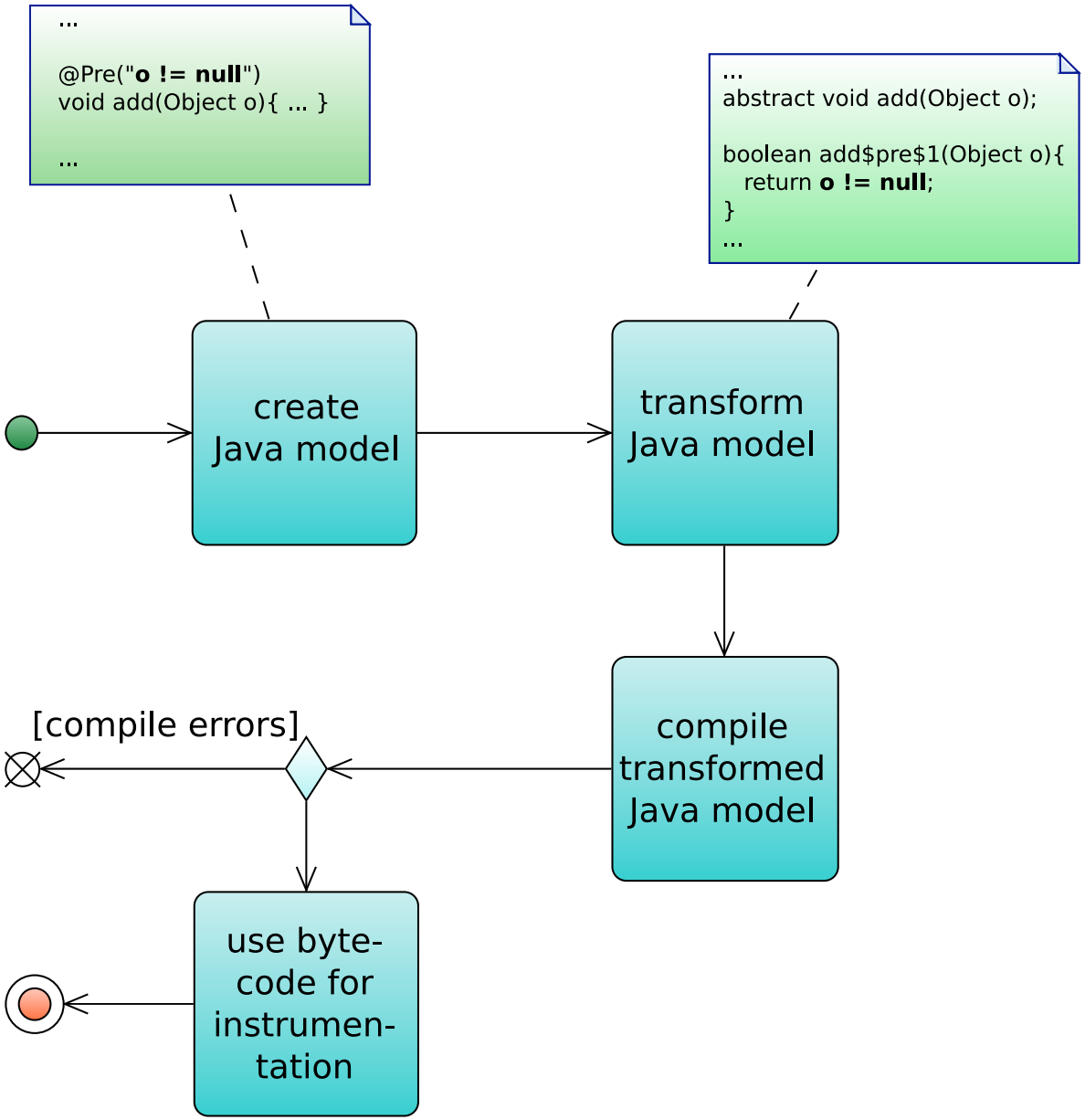

1. Be a Java agent!
2. Create & transform model in the same manner as during contract validation
3. Compile transformed model and keep the generated bytecode
4. Weave the contract bytecode into the running program

⊙ Why are we re-doing steps 1-3?

Enforce Contracts *(runtime)*

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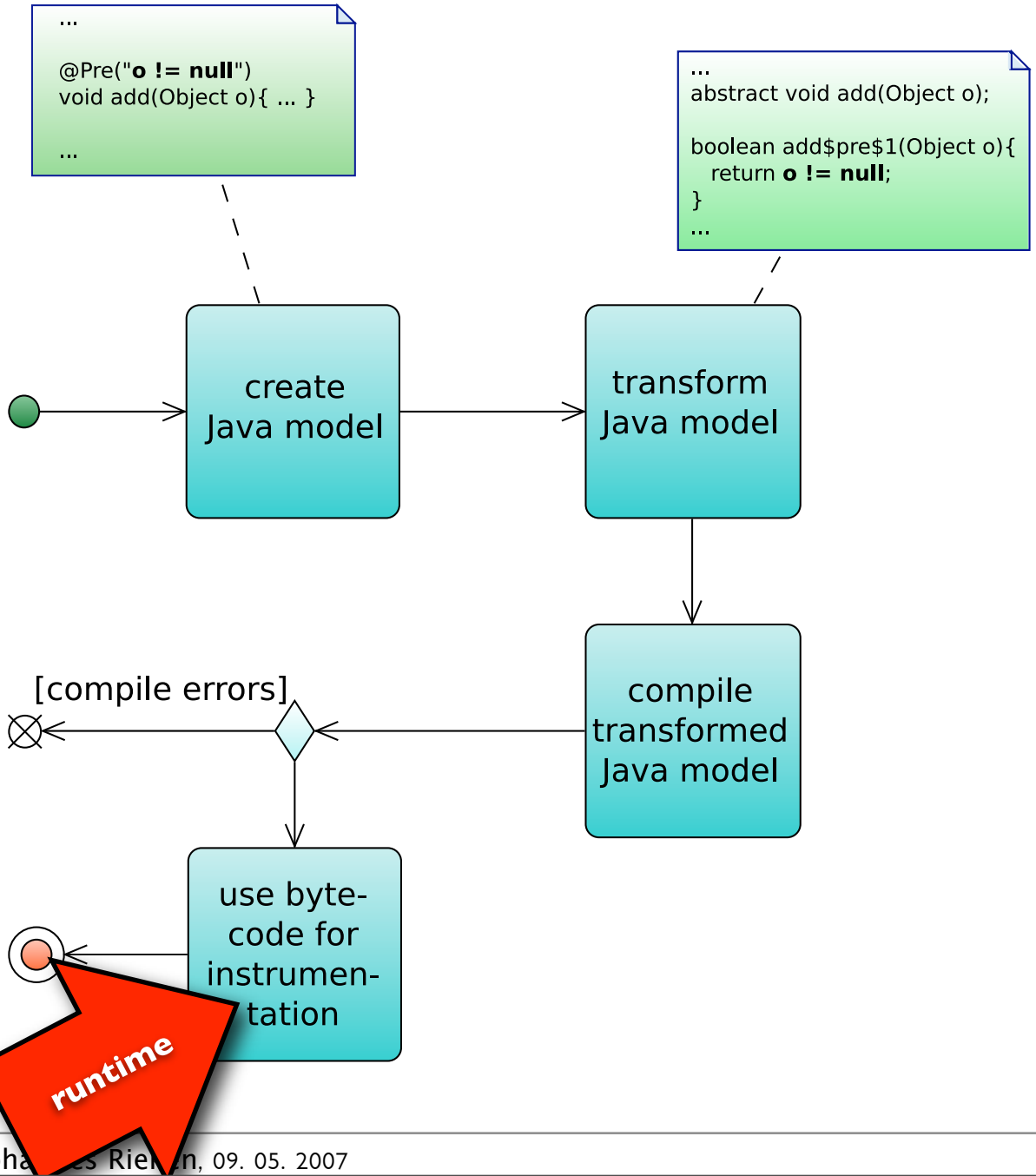

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How it looks

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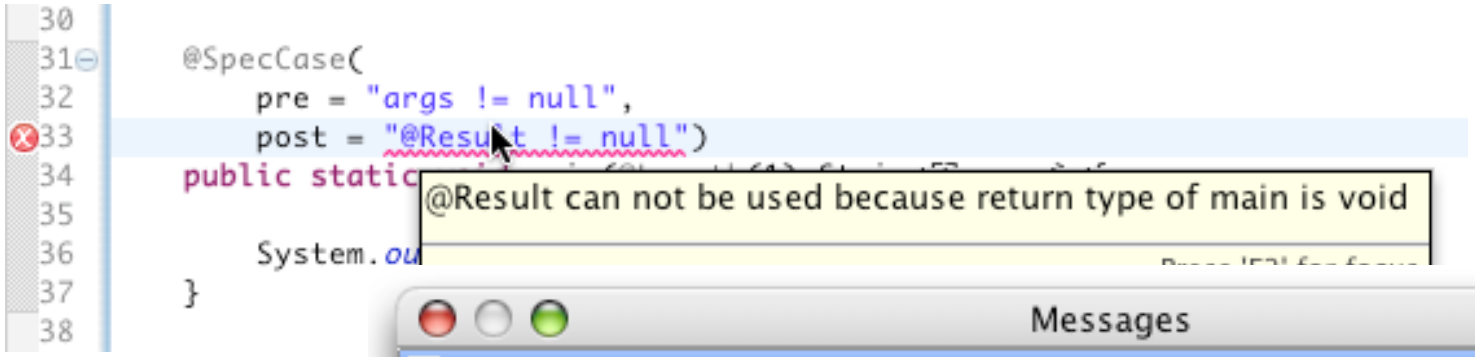

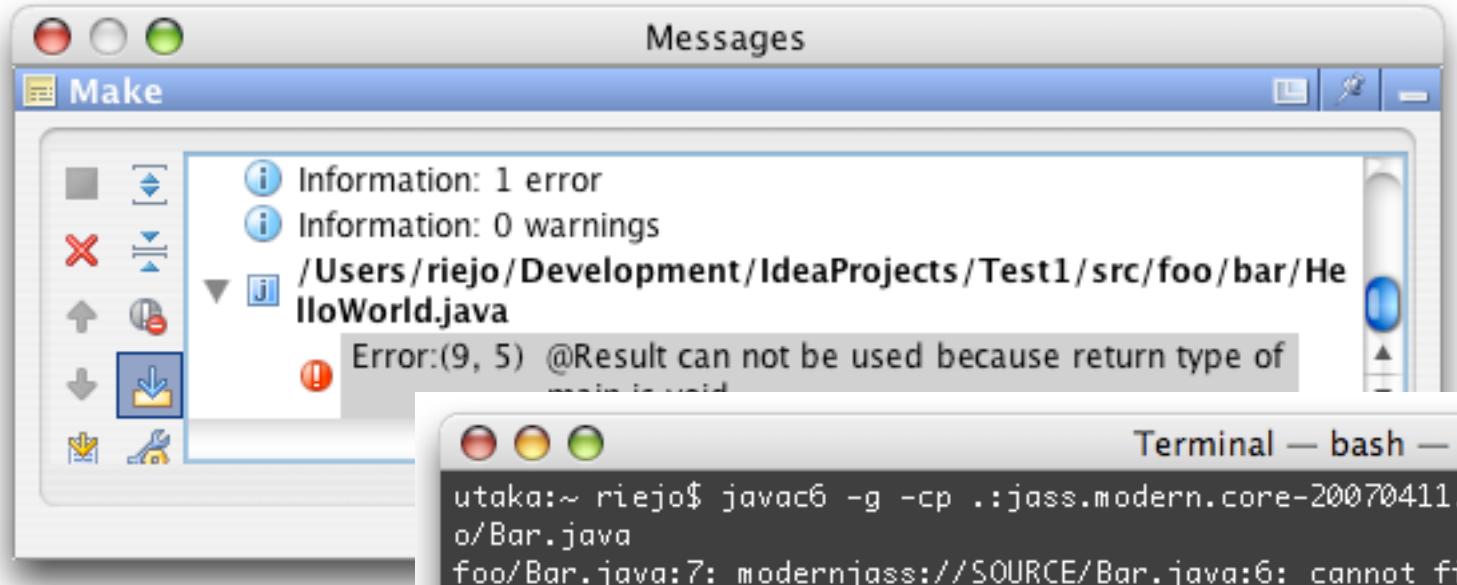

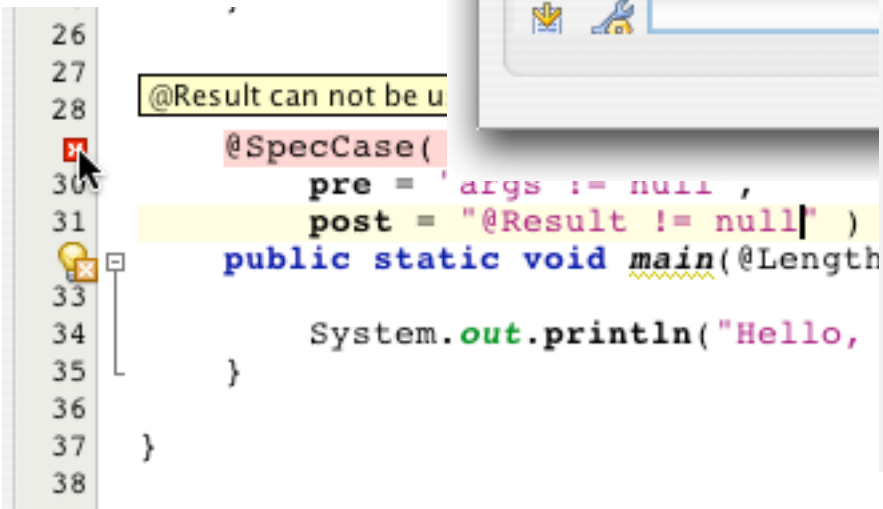

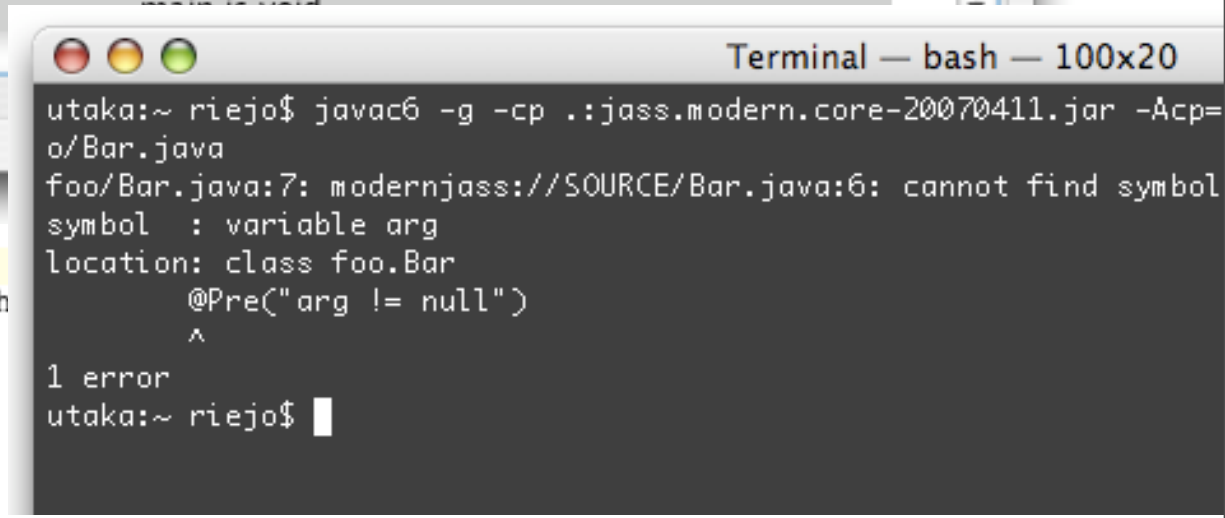

Demo

Features: *Modern Jass*

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- Method Specifications & Invariants (**@SpecCase**, **@Also**, **@Invariant**)
- Model variables (**@Model**, **@Represents**)
- Full support for inheritance of contracts
- Flyweight specifications (**@NonNull**, **@Min**, ...)
- Supports the notion of side-effect freeness (**@Pure**)

- Integrates seamlessly: *Annotation Processor*, *Java Agent*
- Low maintenance costs: *Compiler API*

Limitations *(Concept)*

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- Annotations & Annotation Processing:
  - limited set of annotation targets, e.g. no annotation for loops

```
@Variant(n-i) for( int i; i < a.length; i++){
 ...
 i = someRandomExpression();
}
```

  - waiting for JSR 305, JSR 308
  - Processing for annotated types only
- Bytecode:
  - Missing debug information (parameter names)
  - Line-Number-Table should contain more information
- Implementation of the concept has limitations, too

Future Work

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- Further collaboration with the JML 5 project - unified set of specification annotations
- Improve tool implementation (remove bugs, improve speed)
- Open source everything (*http://modernjass.sourceforge.net*)
- Investigate different implementation approaches, esp. reusing some Eclipse or NetBeans components
- Watch out for upcoming changes: JSR 305, JSR 308, Eclipse: Code-completion for annotation processor, syntax-highlighting in attribute-values

Summary

- The chosen concept is applicable for DBC!
- Rich feature set (can be compared to JML)
- *"Ease of use"* and *"Ease of integration"* (that is something new)
- Prototypic implementation could be used to realise different case studies
- Still, prototype is not for productive use (in parts only)

Thanking you for your kind attention!