Proving Backward Compatibility for Object-Oriented Libraries

Yannick Welsch and Arnd Poetzsch-Heffter

University of Kaiserslautern

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“Interfaces of systems are collections of classes rather than methods”

[Tony Hoare, Meeting of the IFIP WG 1.9, Vienna, 15.7.14]

General motivation

- practical motivation:
  → software maintenance and evolution

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  → software maintenance and evolution
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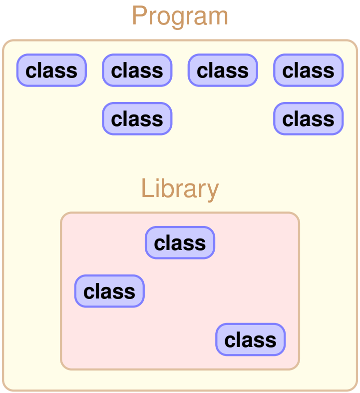
  → behavioral subtyping at the code level
- conceptual motivation:
  → components with complex interfaces

```
package p;

public interface IT { IT m(); }

public class UseIT {
  public IT runM( IT x ) {
    return x.m();
  }
}
```

Overview

- Introduction to backward compatibility
- A fully abstract semantics of LPJava
- Proving backward compatibility

Introduction to backward compatibility



Program

class

class

class

class

class

class

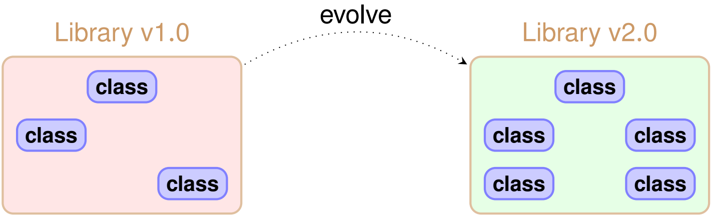
Library

class

class

class

Introduction to backward compatibility



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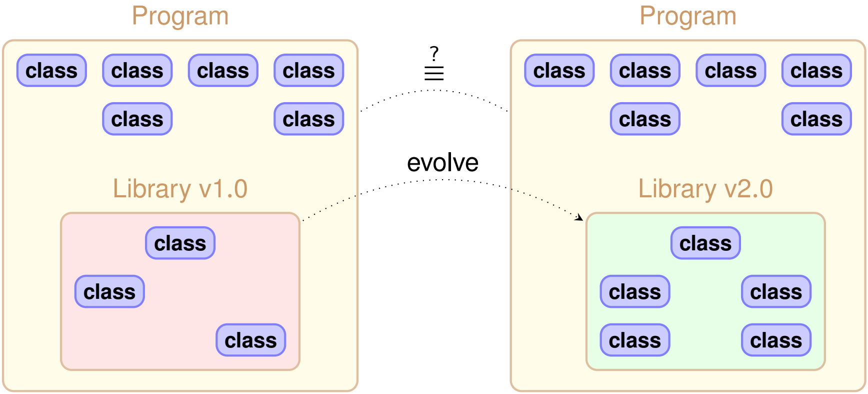

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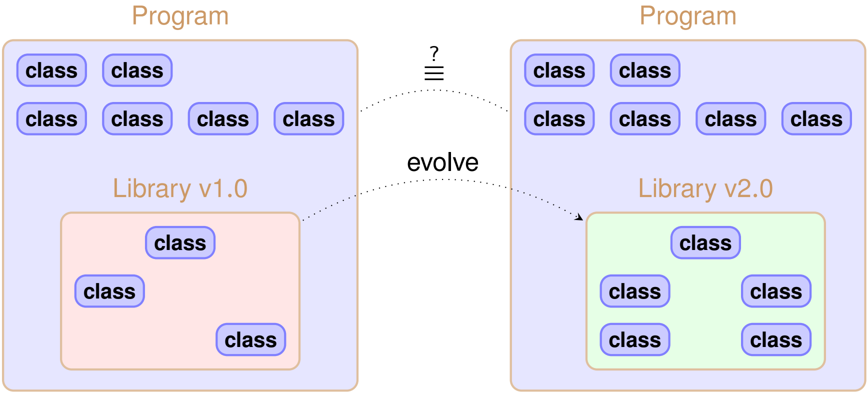

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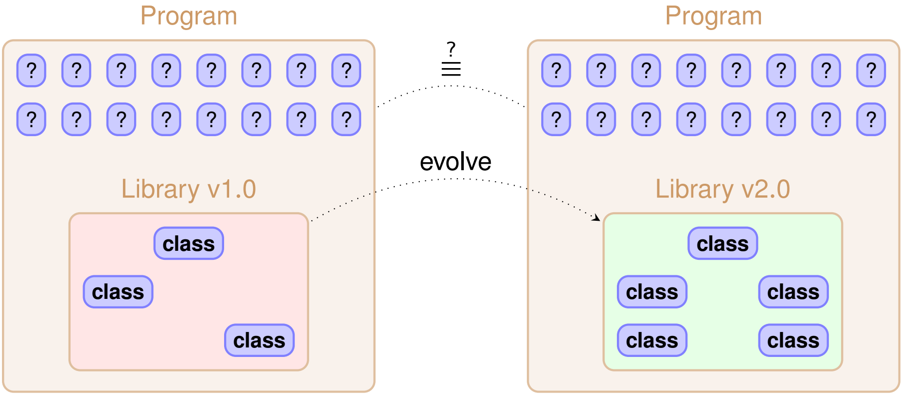

Example: Is library v2.0 backward compatible with v1.0?

Library v1.0

```
package cells;

public interface Val {}

public class Cell {
  private Val v;
  public void set(Val nv) {
    v = nv;
  }
  public Val get() {
    return v;
  }
}
```

Library v2.0

```
package cells;

public interface Val {}

public class Cell {
  private Val v1, v2;
  private boolean f;
  public void set(Val nv) {
    f = !f ;
    if (f) v1 = nv; else v2 = nv;
  }
  public Val get() {
    if (f) return v1; else return v2;
  }
  public Val getPrevious() {
    if (f) return v2; else return v1;
  }
}
```

Backward compatibility: Two aspects

backward compatibility

=

source compatibility

+

behavioral compatibility

Source compatibility: Separation by compiling

Library v1.0

```
package problem1;

interface I {
    ...
}

public abstract class C
            implements I {
    public I f;
    protected C g;
}
```

Library v2.0

```
package problem1;

public class C {
    public D f;
    public C g;
    public C m() { ... }
}

class D {
    ...
}
```

Source compatibility: Separation by used libraries

Library v1.0

```
package problem2;

public class C {
  public p.D f;
}
```

Library v2.0

```
package problem2;

public class C {
  public p.D f;
  private p.E g;
}
```

Behavioral compatibility: Separation by application code

Library v1.0

```
package problem3;

public interface A {
   int m1();
   int m2();
}

public class B implements A {
   public int m1() { return 42; }
   public int m2() { return m2(); }
}
```

Library v2.0

```
package problem3;

public interface A {
   int m1();
   int m2();
}

public class B implements A {
   public int m1() { return 42; }
   public int m2() { return 42; }
}
```

A fully abstract semantics of LPJava

Challenge and approach

Definition (Backward compatibility)

A library Y is **backward compatible** with X if for *any* program context K of X: $KX_{init}\downarrow$ implies $KY_{init}\downarrow$ (adopted from [Morris 68])

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1. Heaps and stacks in program configurations significantly different
2. Infinitely many possible contexts

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1. Heaps and stacks in program configurations significantly different

   → Use trace-based semantics that abstracts from internal representation of library

   ### Theorem (Trace semantics captures all relevant information)

   Y is backward compatible with X if and only if
   for any program context K of X: $Traces(KX) \subseteq Traces(KY)$.

2. Infinitely many possible contexts

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2. Infinitely many possible contexts

   → Construct *most general context* κ_X that simulates all contexts of X

   ### Theorem (Most general context generates all possible behaviors)

   $$Traces(\kappa_X X) = \bigcup_K Traces(KX)$$

Setting - LPJava

$$
\begin{array}{rcl}
K, X, Y & ::= & \overline{Q} \\
Q, R & ::= & \textbf{package}\ p\ ;\ \overline{D} \\
D & ::= & [\textbf{public}]\ \textbf{class}\ c\ \textbf{extends}\ p.c\ \textbf{implements}\ \overline{p.i}\ \{\ \overline{F}\ \overline{M}\ \} \\
 & | & [\textbf{public}]\ \textbf{interface}\ i\ \textbf{extends}\ \overline{p.i}\ \{\ \overline{M}\ \} \\
F & ::= & \textbf{private}\ p.t\ f\ ; \\
M & ::= & \textbf{public}\ p.t\ m(\overline{p.t\ v})\ \Big(\ ;\ \mid\ \{\ E\ \}\ \Big) \\
E & ::= & x \mid \text{null} \mid \text{new}\ p.c() \mid E.f \mid E.f = E \mid E.m(\overline{E}) \\
 & | & \text{let}\ p.t\ x = E\ \text{in}\ E \mid E == E\ ?\ E : E \mid (p.t)E : E \\
t & ::= & c \mid i
\end{array}
$$

where $c \in$ class names, $i \in$ interface names, $p, q \in$ package names, $f \in$ field names, $m \in$ method names and $x \in$ variable names.

From program runs to traces

- Start with standard small-step operational semantics (similar to FJ)
  - $(KX, Heap, Stack) \rightsquigarrow (KX, Heap', Stack')$
- Characterize library behavior by the interactions between code belonging to library (X) and code belonging to program context (K)
- Generate a *label* if control flow passes from K to X or vice-versa
- Augment configurations
- Program runs then generate traces (i.e. sequences of labels)

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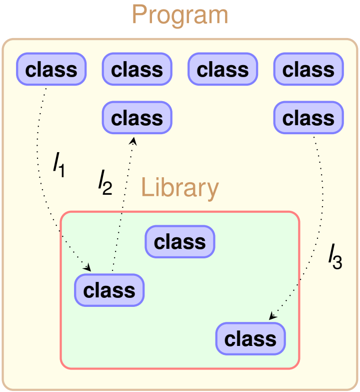

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From program runs to traces

- Start with standard small-step operational semantics (similar to FJ)
- Characterize library behavior by the interactions between code belonging to library (X) and code belonging to program context (K)
- Generate a *label* if control flow passes from K to X or vice-versa
  - Only method calls and returns relevant
  - Label records all relevant information:
    - direction and method name
    - method call / return
    - exposed objects
    - abstraction of types of exposed objects
- Augment configurations
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- Characterize library behavior by the interactions between code belonging to library (X) and code belonging to program context (K)
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- Augment configurations
  - Tag stack frames whether code originates from K or X
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(Simplified) trace examples

```
// Program context K

public class ValueImpl
                implements Val { ... }

public class Main {
  public void main() {
    Cell c = new Cell();
    Val v = new ValueImpl();
    c.set(v);
    Val v2 = c.get();
  }
}
```

```
// Library X

public interface Val {}
public class Cell {
  private Val v;
  public void set(Val nv) {
    v = nv;
  }
  public Val get() {
    return v;
  }
}
```

(Simplified) trace examples

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// Program context K

public class ValueImpl
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public class Main {
  public void main() {
    Cell c = new Cell();
    Val v = new ValueImpl();
    c.set(v);
    Val v2 = c.get();
  }
}
```

```
// Library X

public interface Val {}
public class Cell {
  private Val v;
  public void set(Val nv) {
    v = nv;
  }
  public Val get() {
    return v;
  }
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```

$\text{Traces}(KX) = \{\ \text{call } o_1.\mathit{set}(o_2)$⍗ $\cdot$ $\text{rtrn } \_$⍐ $\cdot$ $\text{call } o_1.\mathit{get}()$⍗ $\cdot$ $\text{rtrn } o_2$⍐ $\}$

(where $o_1 \neq o_2$ are arbitrary object identifier)

(Simplified) trace examples

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// Program context K

public class ValueImpl
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public class Main {
  public void main() {
    Cell c = new Cell();
    Val v = new ValueImpl();
    c.set(v);
    Val v2 = c.get();
  }
}
```

```
// Library Y

public interface Val {}
public class Cell {
  private Val v1, v2;
  private boolean f;
  public void set(Val nv) {
    f = !f ;
    if (f) v1 = nv; else v2 = nv;
  }
  public Val get() {
    if (f) return v1; else return v2;
  } ...
}
```

$$\text{Traces}(KX) = \{\ \text{call } o_1.set(o_2)\downarrow \ \cdot\ \text{rtrn } \_\uparrow \ \cdot\ \text{call } o_1.get()\downarrow \ \cdot\ \text{rtrn } o_2\uparrow\ \}$$

(where $o_1 \neq o_2$ are arbitrary object identifier)

$= \text{Traces}(KY)$

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- Extend LPJava by nondeterministic expression ($E ::= \ldots \mid$ nde)

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- Augment configurations
    - Tag objects whether they have been created by code of *K* or *X*
    - Tag objects whether they have been exposed / internal
- Construction of program context κ_X is solely based on library *X*:

```
public class Main { public void main() { nde; } }

public class Cell_1 extends Cell {}
public class Cell_2 extends Cell { public void set(Val nv) { nde; } }
public class Cell_3 extends Cell { public Val get() { return nde; } }
public class Cell_4 extends Cell {
  public void set(Val nv) { nde; }
  public Val get() { return nde; }
}
...
```

Full abstraction

1. Traces capture all relevant information about the behavior
2. κ_X represents exactly all possible program contexts for X

Theorem (Full abstraction)

Y is backward compatible with X if and only if $Traces(\kappa_X X) \subseteq Traces(\kappa_Y Y)$.

- More details in Welsch/Poetzsch-Heffter. *A fully abstract trace-based semantics for reasoning about backward compatibility of class libraries* (Science of Computer Prog. 92, pp. 129-161, Oct. 2014)
- Related work:
  - Java Jr. (Jeffrey/Rathke 2005)
  - Reasoning about class behavior (Koutavas/Wand 2007)
  - Ownership confinement ensures representation independence for object-oriented programs (Banerjee/Naumann 2005)
  - ...

Proving backward compatibility

Proving backward compatibility and equivalence

Two Approaches

1. Simulation proof based on abstract models:
    - Develop (or mine) abstract models of the libraries
    - Prove models correct vs. code (Hoare-logic)
    - Prove equivalence on the model level
    - First experiences using ITP

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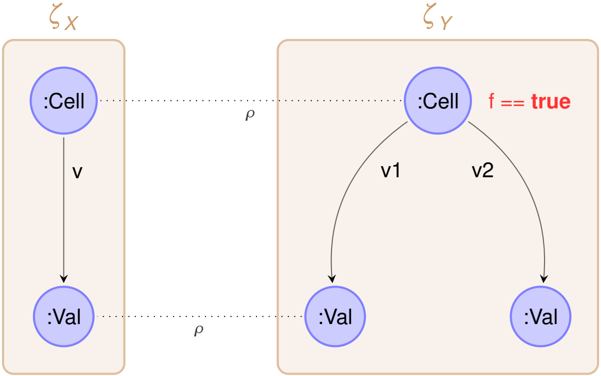
    - Develop (or mine) abstract models of the libraries
    - Prove models correct vs. code (Hoare-logic)
    - Prove equivalence on the model level
    - First experiences using ITP
2. Simulation proof based on coupling relation:
    - Coupling relation between runtime configs of $\kappa_X X$ and $\kappa_X Y$
    - Prove simulation for all possible input messages
    - Automatic checking based on an embedding into Boogie (FTfJP'12)

Coupling relation for Cell example



Specification:

invariant forall old Cell o1, **new** Cell o2 :: o1 ~ o2
==> **if** o2.f then o1.c ~ o2.c1 **else** o1.c ~ o2.c2;

Checking technique and tool

BCVerifier:

- Specification language for coupling invariants

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BCVerifier:

- Specification language for coupling invariants
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- Generate verification conditions for Boogie to prove that coupling invariant is a simulation:
  - Corresponding inputs lead to corresponding outputs
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Remark:

Needs a bit of twisting as Boogie is not designed for simulations

Coupling in Boogie

Coupling invariant:

```
function Inv(heap1:Heap, heap2:Heap, related:Bij) returns (bool) {
  ( forall o1,o2:Ref :: related[o1,o2] && heap2[o2,f]
     ==> RelNull(heap1[o1,c], heap2[o2,c1], related) ) &&
  ( forall o1,o2:Ref :: related[o1,o2] && !heap2[o2,f]
     ==> RelNull(heap1[o1, c], heap2[o2,c2], related) )
}
function RelNull(r1:Ref, r2:Ref, related:Bij) returns (bool) {
  (r1 == null && r2 == null) || (r1 != null && r2 != null && related[r1,r2])
}
```

allows to verify Cell example

BCVerifier example: OneOfLoop

```
public class C {
    public int m(int n){
        int x = 0;
        for(int i=0; i<n; i++){
            x += i;
        }
        return x;
    }
}
```

```
public class C {
    public int m(int n){
        int x = 0;
        int i = 1;
        while(i<n){
            x += i;
            i++;
        }
        return x;
    }
}
```

BCVerifier example: OneOfLoop

```
1  public class C {
2      public int m(int n){
3          int x = 0;
4          for(int i=0; i<n; i++){
5              x += i;
6          }
7          return x;
8      }
9  }
```

```
1  public class C {
2      public int m(int n){
3          int x = 0;
4          int i = 1;
5          while(i<n){
6              x += i;
7              i++;
8          }
9          return x;
10     }
11 }
```

```
local place inLoop1 = line 5 of old C when i > 0;
local place inLoop2 = line 6 of new C;

local invariant at(inLoop1) && at(inLoop2) ==>
      eval(inLoop1, n) == eval(inLoop2, n)
   && eval(inLoop1, x) == eval(inLoop2, x)
   && eval(inLoop1, i) == eval(inLoop2, i);
```

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Aspects for the future:

- Design languages such that source compatibility is automatically checkable
- Develop refined forms of backward compatibility

Questions?