Lecture 4

Towards a Verifying Compiler: Data Abstraction

Wolfram Schulte
Microsoft Research
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Purity, Model fields, Inconsistency

Joint work with Rustan Leino, Mike Barnett, Manuel Fähndrich, Herman Venter, Rob DeLine, Wolfram Schulte (all MSR), and Peter Müller (ETH), Bart Jacobs (KU Leuven) and Bor-Yuh Evan Chung (Berkley) .

Slides based on a presentation of Peter Müller given at MSR 5/2006

Review: Verification of OO Programs with Invariants

- What were the 2 major tricks to support invariants?
- Which programs can we verify?
- What are the limitations?

Data Abstraction using Methods

Needed for

- Subtyping
- Information hiding

```
interface Shape {
 pure int Width( );
 void DoubleWidth( )
  ensures Width( ) == old( Width( ) ) * 2;
}
```

```
class Rectangle: Shape {
 int x1; y1; x2; y2;
 pure int Width( )
   private ensures result == x2 – x1;  { … }
 void DoubleWidth( )
   ensures Width( ) == old( Width( ) ) * 2;
 { … }
}
```

Encoding of Pure Methods

- Pure methods are encoded as functions

$$M\text{: Value} \times \text{Value} \times \text{Heap} \rightarrow \text{Value}$$

- Functions are axiomatized based on specifications

$$\forall \text{this,par,Heap:}$$
$$\quad \text{Requires}_M(\text{ this,par,Heap }) \Rightarrow$$
$$\qquad \text{Ensures}_M(\text{this,par,Heap}) [\ M(\text{this,par,Heap })\ /\ \textbf{result}\ ]$$

Problem 1: Inconsistent Specifications

- Flawed specifications potentially lead to *inconsistent axioms*

- How to guarantee consistency?

```
class Inconsistent {
  pure int Wrong( )
    ensures result == 1;
    ensures result == 0;
  { … }
}
```

```
class List {
  List next;
  pure int Len( )
    ensures result == Len( ) + 1;
  { … }
  … }
```

Problem 2: Weak Purity

- Weak purity can be observed through reference equality
- How to prevent tests for reference equality?

```
class C {
  pure C Alloc( )
    ensures fresh( result );
  { return new C( ); }

  void Foo( )
    ensures Alloc( )==Alloc( );
  { ... }
}
```

$$Alloc(\text{ this},\mathbf{H}\ ) = Alloc(\text{ this},\mathbf{H}\ )$$

Problem 3: Frame Properties

- Result of pure methods depends on the heap

Has(list, o, **H**)

- How to relate invocations that refer to *different heaps?*

```
class List {
  pure bool Has( object o ) { … }
  void Remove( object o )
    requires Has( o );
  { … }
… }
```

```
void Foo( List list, object o )
  requires list.Has( o );
{
  log.Log( “Message“ );
  list.Remove( o );
}
```

Data Abstraction using Model Fields

- Specification-only fields
- Value is determined by a mapping from concrete state
- Similar to parameterless pure methods

```
interface Shape {
 model int width;
 void DoubleWidth( )
  ensures width == old( width ) * 2;
}
```

```
class Rectangle implements Shape {
 int x1; y1; x2; y2;
 model int width | width == x2 – x1;
 void DoubleWidth( )
  ensures width == old( width ) * 2;
 { … }  }
```

Variant of Problem 3: Frame Properties

```
class Legend {
   Rectangle box;  int font;
   model int mc | mc==box.width / font;
  … }
```

```
class Rectangle {
  model int width | width == x2 – x1;
  void DoubleWidth( )
    modifies x2, width;
    ensures width = old( width ) * 2;
    { x2 := (x2 - x1) * 2 + x1; }
  }
```

- Assignment might change model fields of client objects
- Analogous problem for subtypes
- How to synchronize values of model fields with concrete fields?

Validity Principle

```
class List {
  List next;
  invariant list is acyclic;
  model int len | len == (next == null) ? 1 : next.len + 1;
  … }
```

- Only model fields of *valid objects* have to satisfy their constraints

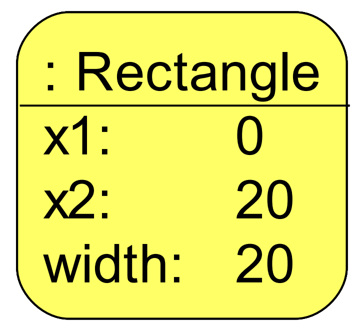
$$\forall X, m: \; X.inv = valid \Rightarrow R_m(X, X.m)$$

- *Avoids inconsistencies* due to invalid objects

Decoupling Principle

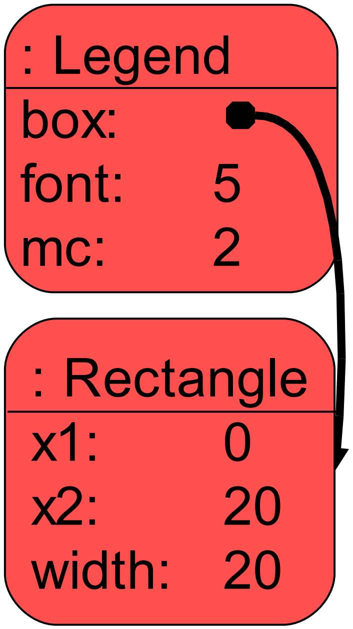
- Decoupling: Model fields are *not updated instantly* when dependee fields are modified
  - Values of model fields are *stored in the heap*
  - *Updated when* object is being *packed*

```
class Rectangle {
  model int width | width == x2 – x1;
  void DoubleWidth( ) requires inv==valid; {
    unpack this;
      x2 := (x2 – x1) * 2 + x1;
    pack this;
  }
```



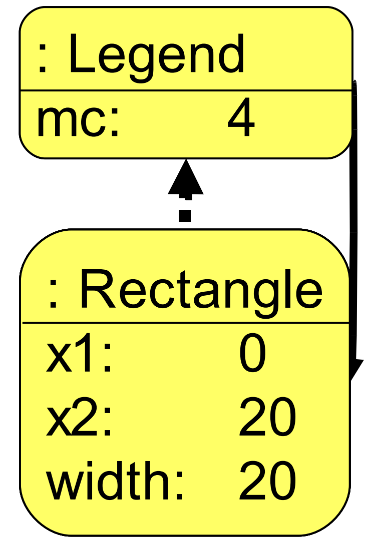
Mutable Dependent Principle

- Mutable Dependent: If a model field *o.m* depends on a field *x.f*, then *o must be mutable whenever x is mutable*



The Methodology in Action

```
class Rectangle {
 void DoubleWidth( )
  requires inv == valid &&
                 owner.inv == mutable;
  modifies width, x2;
 {
  expose(this) {
     x2 := (x2 – x1) * 2 + x1;
  }
 }
```




```
class Legend {
 rep Rectangle box;
 model int mc |
     mc == box.width / font;
 … }
```

Automatic Updates of Model Fields

pack X ≡
    assert $X \neq$ **null** $\wedge$ X.inv = mutable;
    assert Inv(X);
    assert $\forall$p: p.owner = X $\Rightarrow$ p.inv = valid; …
    X.inv := valid;
    foreach m of X:
        assert $\exists$r: R_m(X, r);
        X.m := **choose** r **such that** R_m(X, r);
    end

Soundness

- Theorem:

$$\forall X,m:\ \ X.inv = valid \Rightarrow R_m(\ X,\ X.m\ )$$

- Proof sketch
  - Object creation new:
    - new object is initially mutable
  - Field update X.f := E;
    - Model fields of X: asserts X.inv = mutable
    - Model fields of X's owners: mutable dependent principle
  - unpack X:
    - changes X.inv to mutable
  - pack X:
    - updates model fields of X

Problem 1 Revisited: Inconsistent Specifications

- Witness requirement for non-recursive specifications
- Ownership for traversal of object structures
- Termination measures for recursive specs

```
pure int Wrong( )
  ensures result == 1;
  ensures result == 0;
```

```
pure int Len( )
  ensures result == Len( ) + 1;
  measured_by height( this );
```

```
pure static int Fac( int n )
  requires n >= 0;
  ensures result ==
    ( n==0 ) ? 1 : Fac( n-1 ) * n;
  measured_by n;
```

Problem 2 Revisited: Restricted Weak Purity

- Pure methods must not return references to new objects (Compile time effect analysis)

```
pure C Alloc( )
{ return new C( ); }
```

- Provide value types for sets, sequences, etc.

Problem 3 Revisited: Frame Properties

- Model field solution does not work for methods with parameters
- Caching of values not possible for runtime checking
- Mutable dependent principle too strict

```
class List {
  pure bool Has( object o )
  { … }
  void Remove( object o )
    requires Has( o );
  { … }
… }
```

```
void Foo( List list, object o )
  requires list.Has( o );
{
  log.Log( “Message“ );
  list.Remove( o );
}
```

Summary

- Data abstraction is crucial to express functional correctness properties
- Verification methodology for model fields
  - Supports subtyping
  - Is modular and sound
  - *Key insight: model fields are reduced to ordinary fields with automatic updates*
- Verification methodology for methods (not yet ready)
  - Partial solution: encoding, weak purity, consistency
  - Future work: frame properties based on effects