Support for Supertype Abstraction in JML

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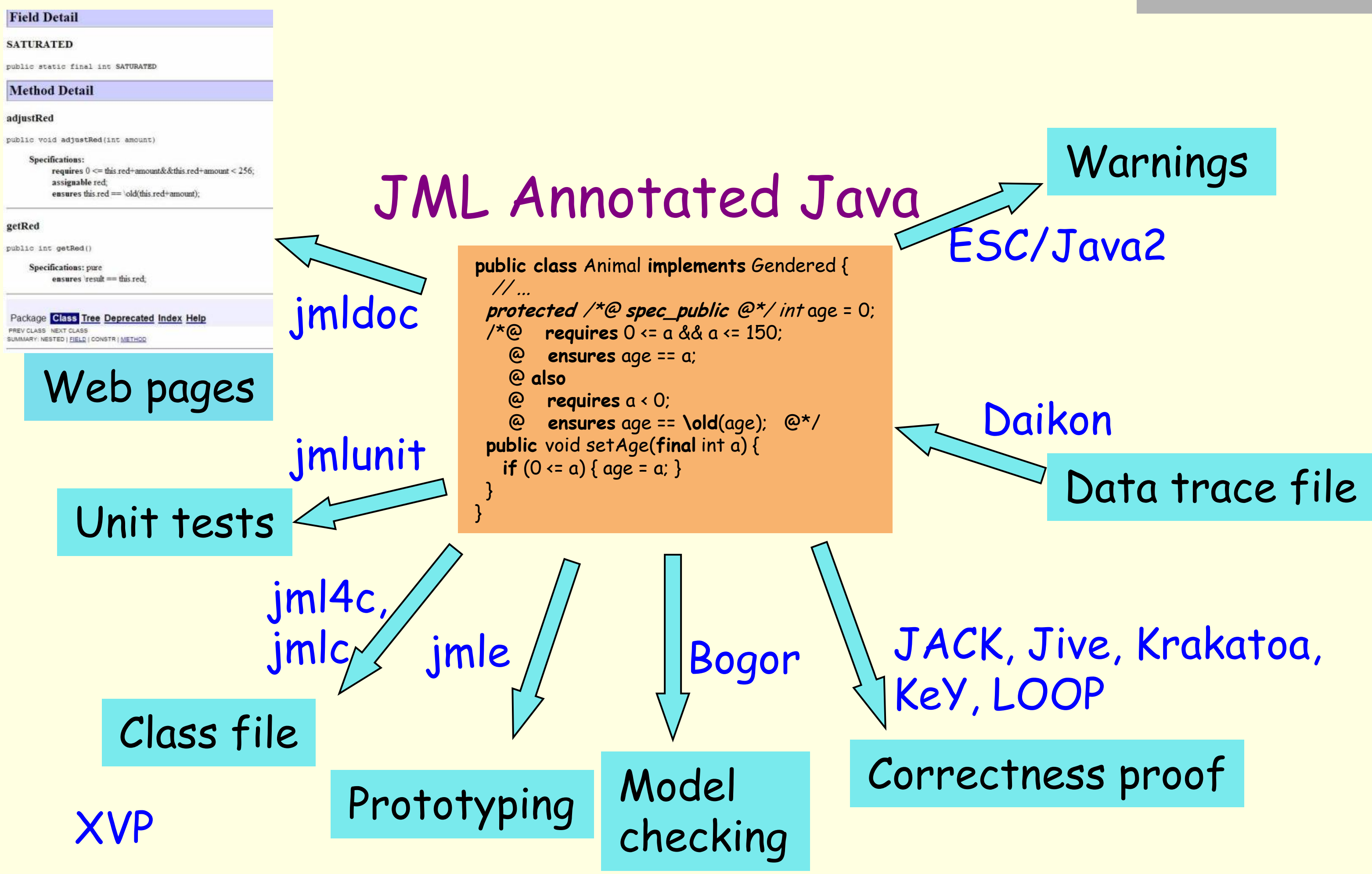
Outline

- JML Background
- Modular reasoning with supertype abstraction

Java Modeling Language—JML

- Formal specification language for Java
  - Functional behavior
  - Sequential
- Goals:
  - Practical, effective for detailed designs
  - Existing code
  - Wide range of tools
- Hoare-style (Contracts)
  - Method pre- and postconditions
  - Type invariants

Many Tools, One Language



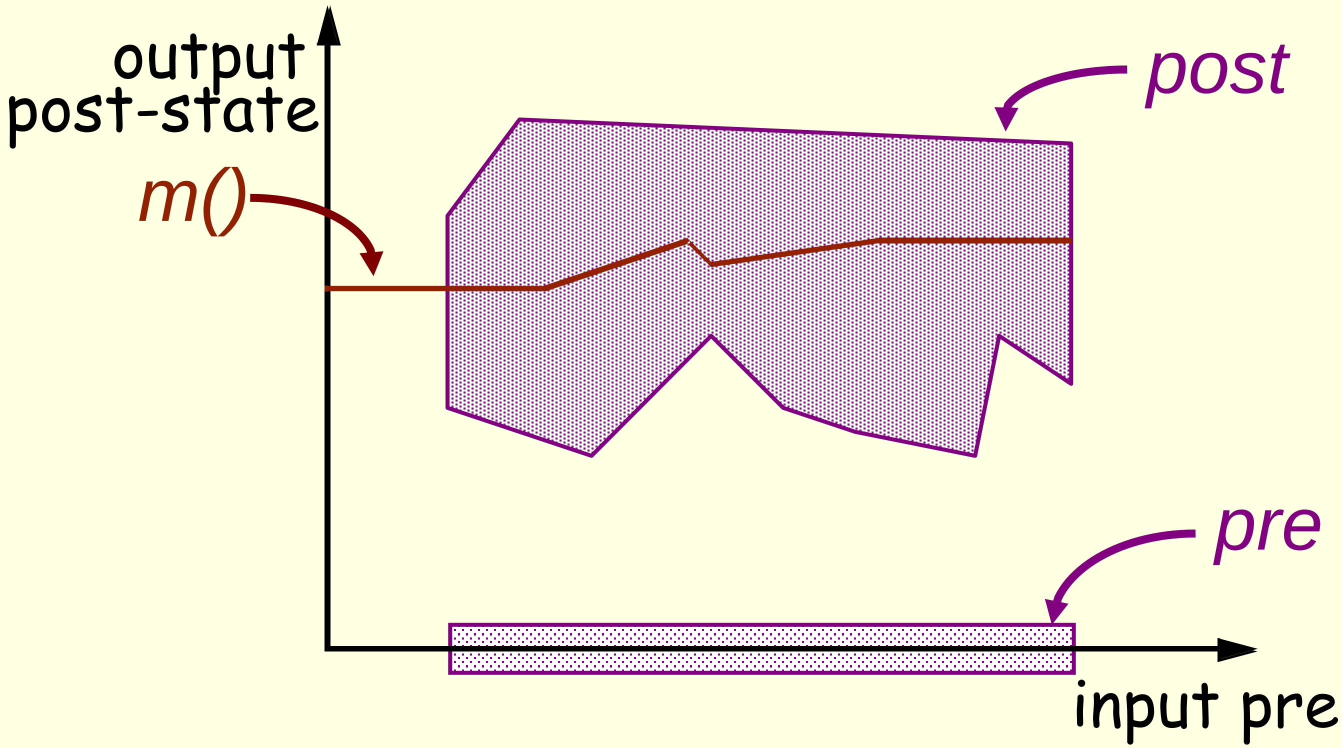
Example JML Specification

```
public interface Gendered {
  //@ model instance String gender;

  //@ requires true;
  //@ ensures \result == gender.equals("female");
  /*@ pure @*/ boolean isFemale();
}
```

model field specification

method behavior specification

Model of Method Specifications



T ▹ (*pre*, *post*)

Specification of Model Field

```
public interface Gendered {
  //@ model instance String gender;

  //@ requires true;
  //@ ensures \result == gender.equals("female");
  /*@ pure @*/ boolean isFemale();
}
```

Implementation of Model Field

```
public class Animal implements Gendered, /*…*/ {
  protected boolean gen; //@ in gender;
  /*@ protected represents gender
    @                <- (gen ? "female" : "male");
    @*/
   public /*@ pure @*/ boolean isFemale()
   { return gen; }
   // …
```

correctness

Problem: Modular Reasoning with Subtyping and Dynamic Dispatch

Reasoning about dynamic dispatch:

```
Gendered e = (Gendered)elems.next();
if (e.isFemale()) {
    //@ assert e.gender.equals("female");
    // ...
}
```

- e could be any subtype (Animal, ...)
- Different implementations
- Different specifications

Problem: Modularity

Reasoning about dynamic dispatch:

```
Gendered e = (Gendered)elems.next();
if (e.isFemale()) {
    //@ assert e.gender.equals("female");
    // ...
}
```

- Verify for each subtype?
- Subtypes may be added later!

Methodology: Supertype Abstraction

Reason using static type information:

```
Gendered e = (Gendered)elems.next();
if (e.isFemale()) {
    //@ assert e.gender.equals("female");
    // ...
}
```

- Use specification from Gendered
- As if no subtyping

Modularity of Supertype Abstraction

- Client reasoning ignores subtyping
- Implementations must be behavioral subtypes

More Details: Supertype Absraction in General

Use static type's specifications to reason about:

- Method calls,
- Invariants,
- History constraints,
- Initially predicates

Supertype Abstraction in General

T o = */* create a new object */;*

//@ **assume** o.ext_inv^T;

/ … */*

//@ **assert** o.$ext\_pre^T_m$;
o.m();
//@ **assume** o.$ext\_post^T_m$ && o.ext_inv^T ;

Supertype Abstraction's Soundness

Valid if:

- Invariants etc. hold as needed (in pre-states), and
- Each subtype is a behavioral subtype

Validity of Supertype Abstraction: Client (Supertype) view

T o = */* create a new object */*;

//@ **assume** o.*ext_inv*^{T};

/ … */*

//@ **assert** *o.ext_pre*^T_m ;

o.m();

//@ **assume** *o.ext_post*^T_m && o.*ext_inv*^{T};

Validity of Supertype Abstraction: Implementation (Subtype) View

/* *body of constructor of* T' */

//@ **assert** o.$ext\_inv^{T'}$;

/* … */

//@ **assume** o.$ext\_pre_m^{T'}$ && o.$ext\_inv^{T'}$;
/* *body of* o.m(); */
//@ **assert** o.$ext\_post_m^{T'}$ && o.$ext\_inv^{T'}$;

Behavioral Subtyping for JML

Suppose $T' \leq T$. Then

T' is a strong behavioral subtype of T

if and only if

whenever **this** has type T':

$$ext\_inv^{T'} \Rightarrow ext\_inv^{T},$$

and for all instance methods *m* of T

$$ext\_spec_m^{T'} \sqsupseteq^{T'} ext\_spec_m^{T}$$

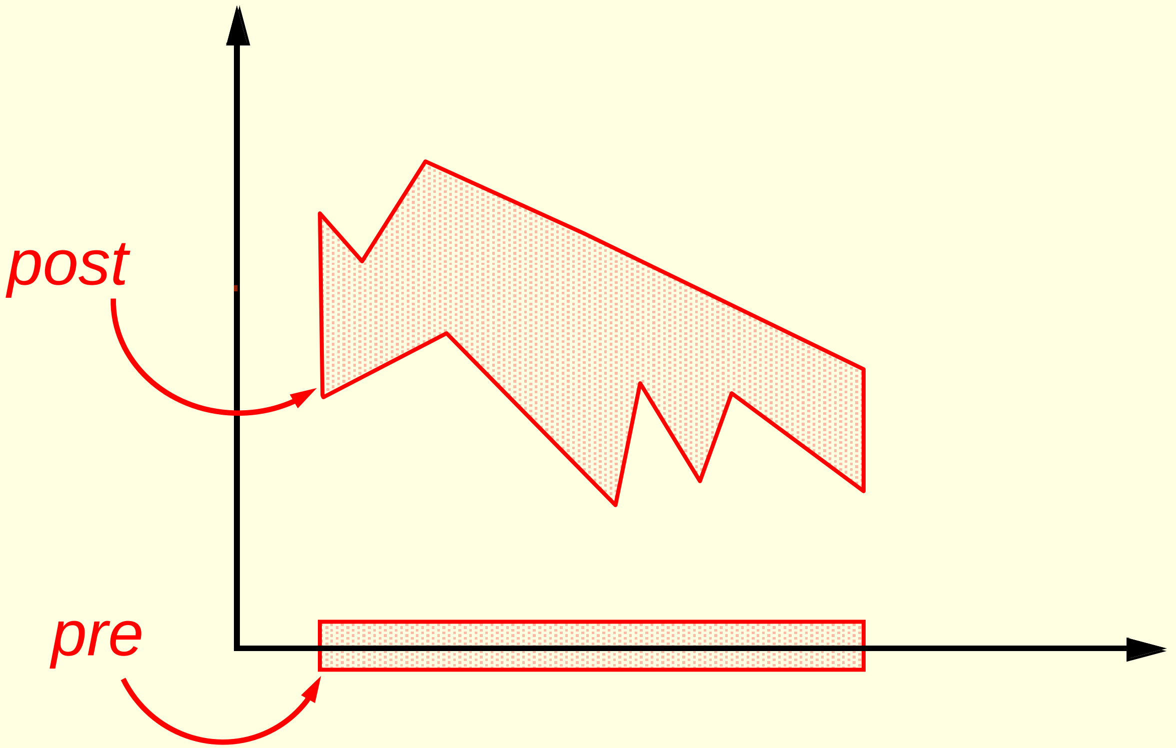
Method Specification Refinement with respect to T'

Notation:

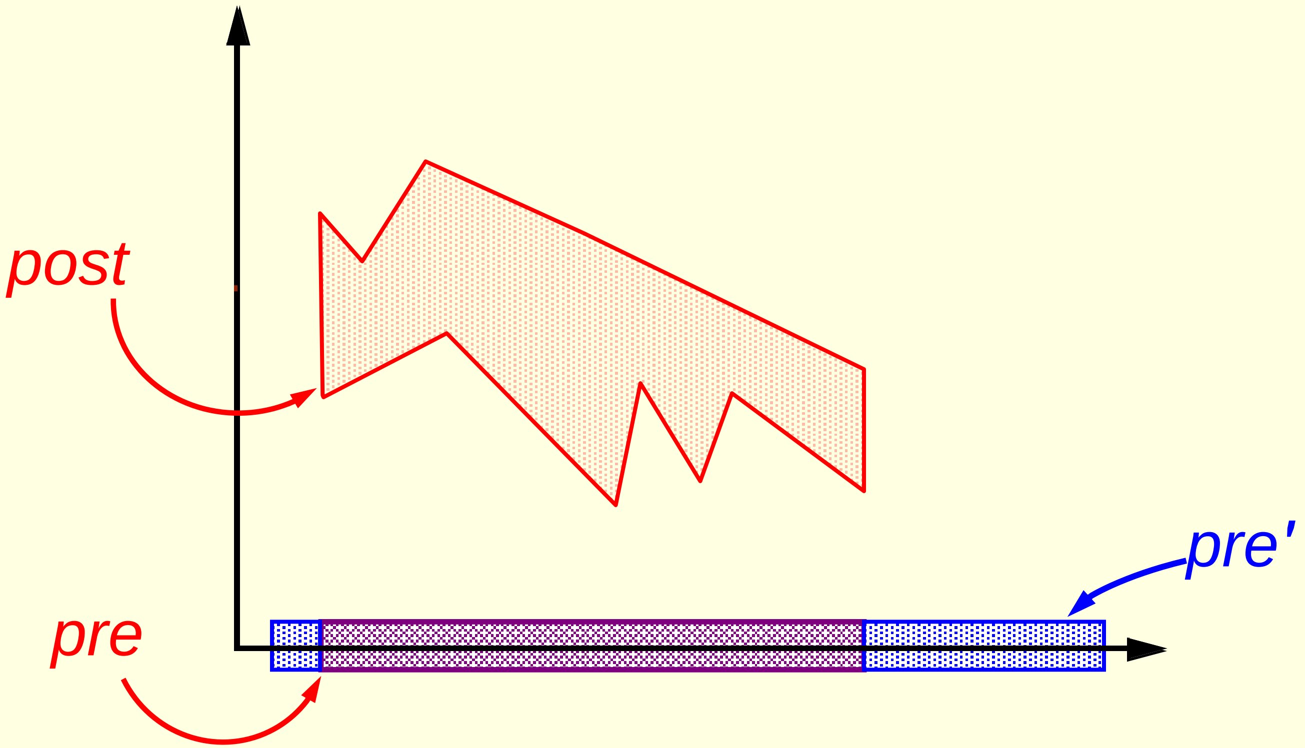
$$(pre', post') \sqsupseteq^{T'} (pre, post)$$

details

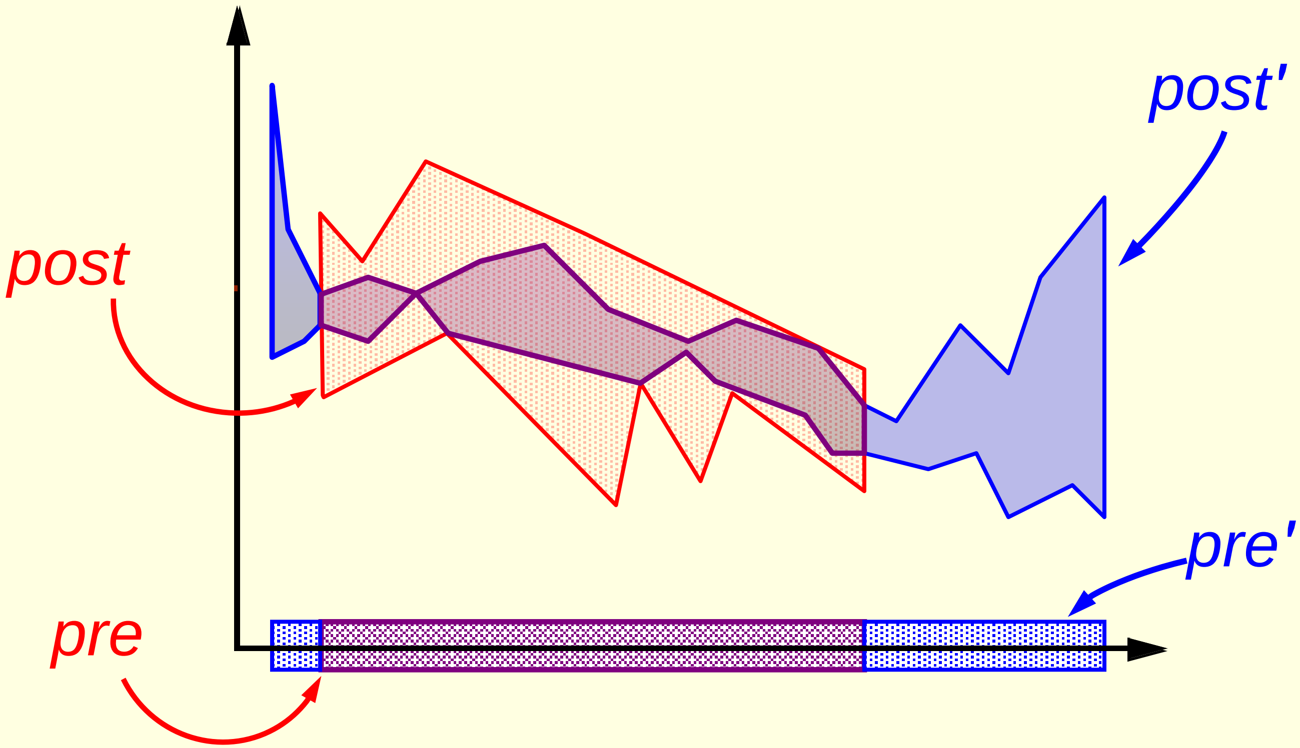
Refinement with respect to T'



Refinement with respect to *T′*



Refinement with respect to T'



Proving Method Refinements

Theorem 1. Suppose $T' \leq T$, and $T' \triangleright (pre', post')$, $T \triangleright (pre, post)$ specify m.

Then $(pre', post') \sqsupseteq^{T'} (pre, post)$

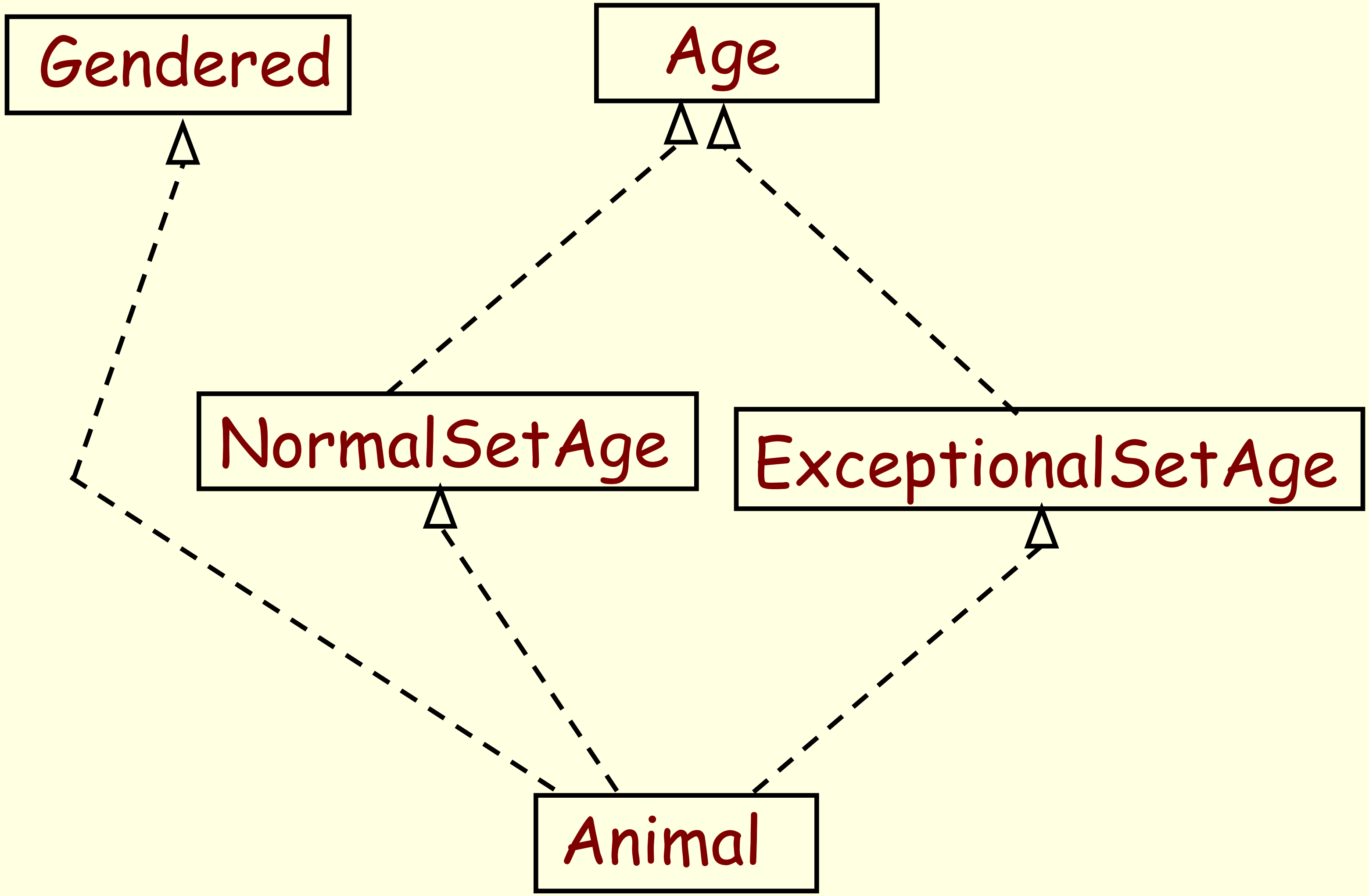
if and only if:

$$Spec(T') \vdash pre \;\&\&\; (\textbf{this instanceof } T') \Rightarrow pre',$$

and

$$Spec(T') \vdash \textbf{\textbackslash old}(pre \;\&\&\; (\textbf{this instanceof } T')) \Rightarrow (post' \Rightarrow post).$$

Subproblem: Avoiding Proofs by Specification Inheritance



Age and NormalSetAge

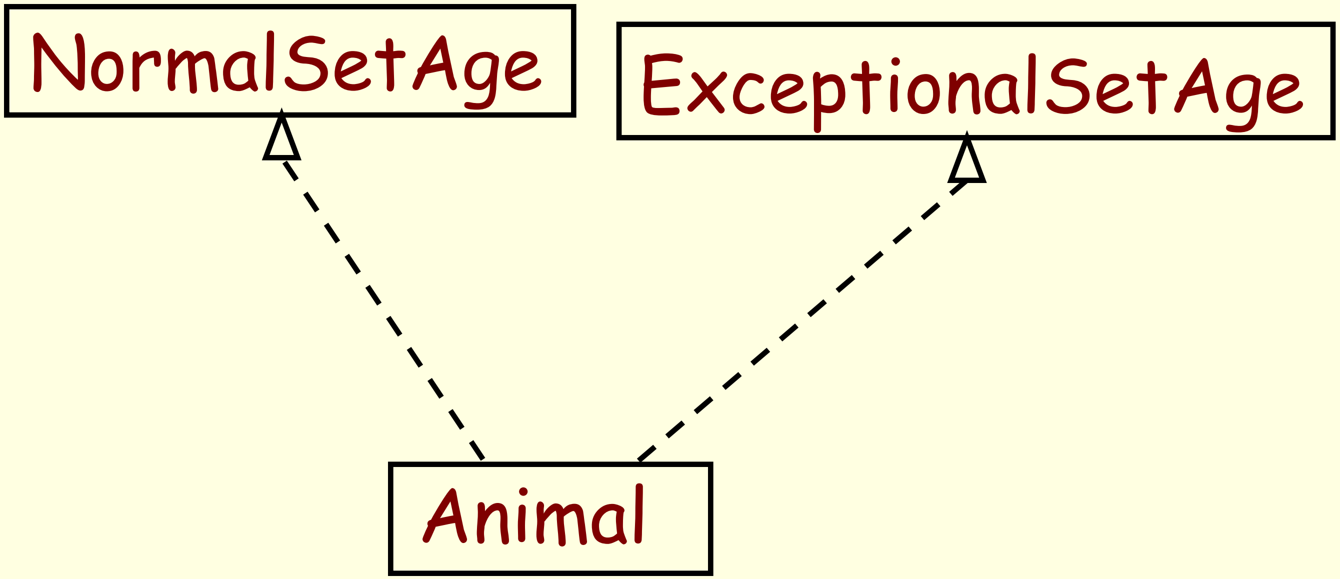
```
public interface Age {
  //@ model instance int age;
}

public interface NormalSetAge implements Age {
  /*@ requires 0 <= a && a <= 150;
    @ ensures age == a;   @*/
  public void setAge(final int a);
}
```

ExceptionalSetAge

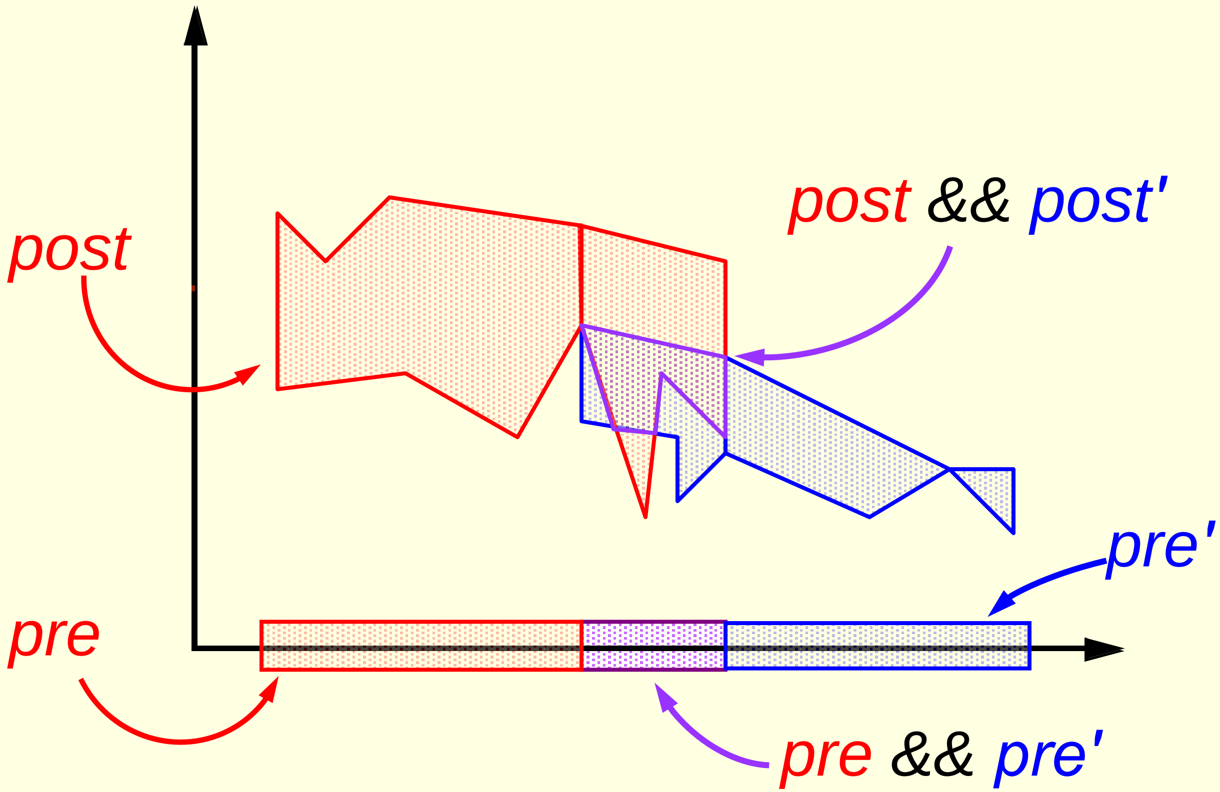
```
public interface ExceptionalSetAge
                                    implements Age {
  /*@  requires a < 0;
     @  ensures age == \old(age);  @*/
  void setAge(final int a);
}
```

What about Animal?

- It's both
- Should obey both specifications



Join of Specification Cases



Join of Specification Cases, 'also'

```
requires 0 <= a && a <= 150;
ensures age == a;
also
requires a < 0;
ensures age == \old(age);
```

means

```
requires (0 <= a && a <= 150) || a < 0;
ensures (\old(0 <= a && a <= 150) ==> age == a)
     && (\old(a < 0) ==> age == \old(age));
```

Join of Specification Cases, $\sqcup^S$

If $T' \triangleright (pre', post')$, $T \triangleright (pre, post)$, $S \leq T'$, $S \leq T$,

then

$$(pre', post') \sqcup^S (pre, post)$$
$$= (p, q)$$

where $p = pre' \mathbin{||} pre$

and q = (\old(pre') ==> $post'$)
&& (\old(pre) ==> $post$)

and $S \triangleright (p, q)$

Model of Inheritance
T's Added Specifications

Declared in *T* (without inheritance):

$added\_inv^T$ invariant

$added\_spec_m^T$ *m*'s specification

Other Notations

$supers(T) = \{U \mid T \leq U\}$

$methods(\mathcal{T}) = \{\, m \mid m \text{ declared in } T \in \mathcal{T}\,\}$

Specification Inheritance's Meaning: Extended Specification of *T*

- **Methods**: for all $m \in methods(supers(T))$

$$ext\_spec_m^T = \sqcup^T \{ added\_spec_m^U \mid U \in supers(T) \}$$

- **Invariant:**

$$ext\_inv^T = \wedge \{ added\_inv^U \mid U \in supers(T) \}$$

also Makes Refinements

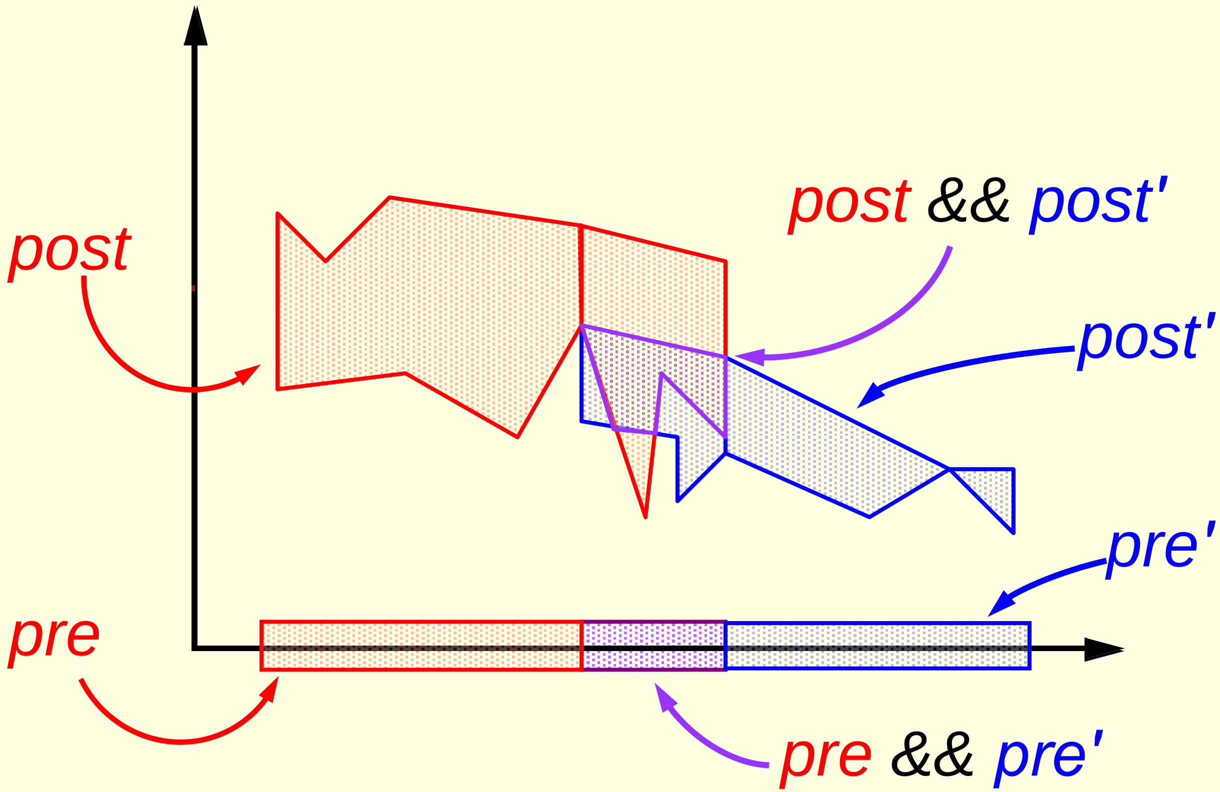
Theorem 2. Suppose **\old** is monotonic.
Suppose $T' \leq T$, and
$T' \triangleright (pre', post')$, $T \triangleright (pre, post)$ specify m.

Then

$$(pre', post') \sqcup^{T'} (pre, post) \sqsupseteq^{T'} (pre, post).$$

Proof: use Theorem 1.

also Makes Refinements



Specification Inheritance Forces Behavioral Subtyping

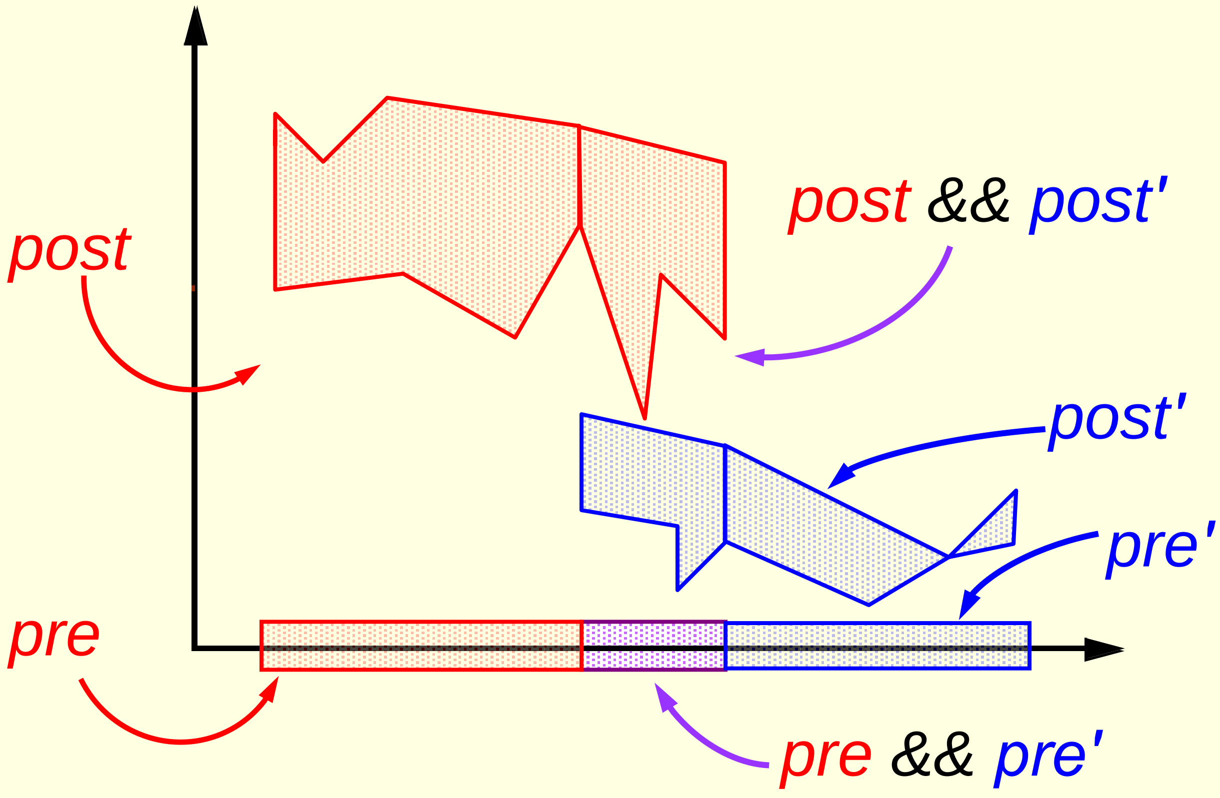
Theorem 3. Suppose $T' \leq T$. Then the extended specification of T' is a strong behavioral subtype of the extended specification of T.

Proof: Use Theorem 2 and definition of extended specification.

Discussion

- Every subtype inherits
- Every subtype is a behavioral subtype
  - Not all satisfiable
  - Supertype must allow refinement

Unsatisfiable Refinements



example

Older Related Work

- Wills's Fresco [Wil92] introduced specification inheritance.
- Wing's dissertation [Win83] combined specification cases like **also**.
- Eiffel [Mey97] has behavioral subtyping and a form of specification inheritance.
- America [Ame87] [Ame91] first proved soundness with behavioral subtyping.
- See survey with Dhara [LD00].

Conclusions

- Supertype abstraction allows modular reasoning.
- Supertype abstraction is valid if:
  - methodology enforced, and
  - subtypes are behavioral subtypes.
- JML's **also** makes refinements.
- Specification inheritance in JML forces behavioral subtyping.
- Supertype abstraction automatically valid in JML.

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