

Interface Inheritance: Behavioral Subtyping

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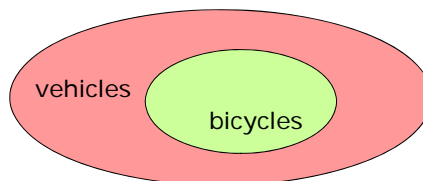
Lecture 11

Intuition

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- Some interfaces have significant overlap in functionality
 - bicycles and vehicles
 - both have owners and both can move
 - students and persons
 - both have names and both can be selected for juries
 - rectangles and shapes
 - both have a color
- These are all examples of an “is a” relationship
 - This is a common (but poor) intuitive litmus test
- Interfaces define types, ie *sets* of possible values

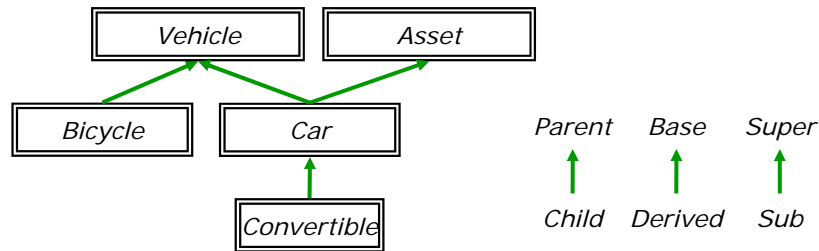
Every bicycle
is a vehicle



Extending Interfaces

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- One interface can extend another
`interface X extends A, B { . . . }`
 - X implicitly includes all methods declared in A, B, and transitively above A and B



Recall: Narrowing vs Widening

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- Recall primitive types (eg long, int)
- Widening
 - Assign a “small” value to a variable of “big” type
 - This is always ok and so can be done implicitly

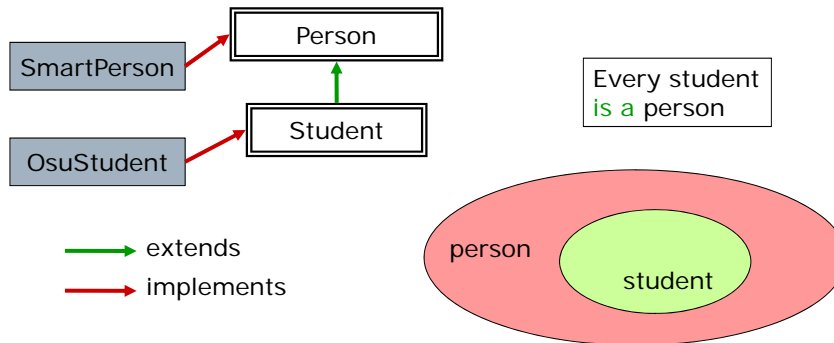
```
void f(int i) {  
    long x = i; //widening: always ok
```
- Narrowing
 - Assign a “big” value to a variable of “small” type
 - The correctness of this cannot be checked by compiler and so requires an explicit cast

```
void f(long x) {  
    int i = x; //narrowing: compile error  
    int j = (int)x; //ok? programmer promise!
```

Narrowing and Widening Objects

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- Subinterfaces are “smaller” types than superinterfaces



Narrowing and Widening Objects

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- Widening
 - Assign a *subinterface* (declared type) to a variable of *superinterface* (declared) type
 - This is always ok and so can be done implicitly

```
void f(Student s) {
    Person p = s; //widening: always ok
```
- Narrowing
 - Assign a *superinterface* (declared) type to a variable of *subinterface* (declared) type
 - This can not be checked by the compiler and so requires an explicit cast

```
void f(Person p) {
    student s = p; //compiler complains
    Student s = (Student)p; //ok? prg promise!
```

Argument Passing

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- Method argument declared types must match signature

```
interface Course {  
    void enroll(Student s) { . . . }  
}  
interface Jury {  
    void select(Person p) { . . . }  
}
```

- Automatic (implicit) widening

```
Student s = ...;  
cse421.enroll(s); //ok (exact match)  
someJury.select(s); //ok (automatic widening)
```

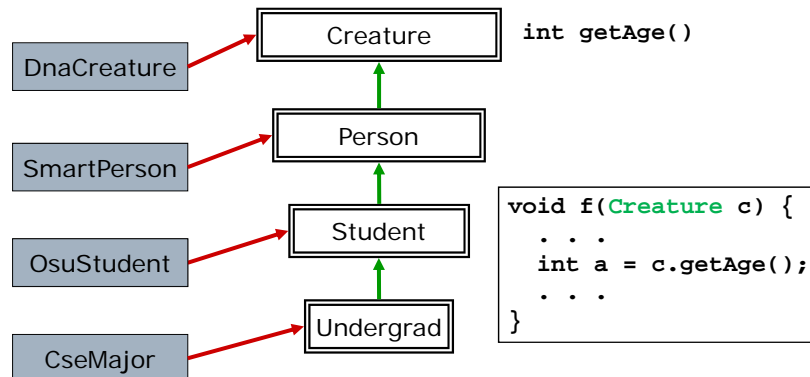
- Cast for (explicit) narrowing

```
Person p = ...;  
someJury.select(p); //ok (exact match)  
cse421.enroll(p); //compiler complains (narrowing)  
cse421.enroll((Student)p); //ok? programmer promise!
```

Simple Rule

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- A variable / parameter of **declared** type T can refer to an object of **dynamic** type "at or below" T



The Problem

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- Compiler enforces only:
 - Method *signatures* match in sub/super interfaces
- Not enforced by compiler:
 - Method *specifications* match
 - *Mathematical models* match
 - *Constraint* match
- That is, a subinterface can change the description of a method's behavior!

BigNatural and BigInteger

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```
//@mathmodel integer n    //@mathmodel integer n
//@constraint n >= 0      //@constraint
interface BigNatural {    interface BigInteger {

    //@alters n            //@alters n
    //@ens n = #n+1       //@ens n = #n+1
    void increment();     void increment();

    //@alters n            //@alters n
    //@ens n=max(0,#n-1)  //@ens n = #n-1
    void decrement();     void decrement();
}                          }
```

BigNatural With Inheritance

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```
//@mathmodel integer n    //@mathmodel integer n
//@constraint n >= 0      //@constraint
interface BigNatural {   interface BigInteger {
    extends BigInteger

                                //@alters n
                                //@ens n = #n+1
                                void increment();

                                //@alters n
                                //@ens n = #n-1
                                void decrement();
}                                }

    //@alters n
    //@ens n=max(0,#n-1)
    void decrement();
}
```

Why Is This a Problem?

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- These changes can break client code!
- Consider:

```
    //@ensures i = #i
void skip(BigInteger i) {
    i.decrement();
    i.increment();
}
```
- The skip method
 - Is correct for BigInteger
 - Is not correct for BigNatural
- But Java allows skip to be called with a BigNatural argument (if BigNatural is a subinterface of BigInteger)

Dealing With This Problem

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- Resolve/C++ approach:
 - Extensions *can only* add new operations
 - Extensions *can not* change the model or specs of extended component
- Alternative: Behavioral subtyping
 - Allow changes to method specs
 - Require new specs to be consistent with specs of extended component
- Beware:
 - Getting behavioral subtyping right is tricky and, even then, subtle problems can arise
 - More conservative approach is safer

Behavioral Subtyping

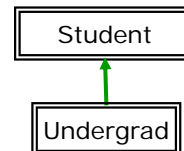
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- Informally, A is a *behavioral subtype* of B when it does everything B does (and maybe more)
 - Everywhere a B is expected, an A can be used instead
- Must satisfy the Substitution Principle:
 - *Any* correct client that uses a B is *still correct* when given an A instead
- Example:
 - A class uses Creature (eg void foo(Creature c))
 - Actual argument might be a Creature, Person, Student, or Undergrad
 - Implementation of foo() should still be correct!
- Note: This is a requirement on the component provider (of A), *not* on the client

Substitution Principle

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- If Undergrad **is** a subtype of Student
 - *Any* correct client of Student is still correct when given an Undergrad
- If Undergrad **not** a subtype of Student
 - There exists *some* correct client of Student that is no longer correct when given an Undergrad



Behavioral Subtyping Rules

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- Subtype constraint \Rightarrow supertype constraint
 - Hence the informal “is a” litmus test
 - This condition alone, however, is not sufficient
- Each method in subinterface:
 - Requires *less* than in superinterface
 - Must work under more conditions
 - Add disjuncts (or) to requires clause
 - “contravariance of arguments”
 - Ensures *more* than in superinterface
 - Must guarantee more to client
 - Add conjuncts (and) to the ensures clause
 - “covariance of return”

More Formally...

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- A's constraint is "stronger"
 - $Inv_A \implies Inv_B$
- For each method, A "requires less"
 - $Pre_A^f \leq Pre_B^f$
 - $Pre_A^g \leq Pre_B^g$
- For each method, A "ensures more"
 - $(Post_A^f \wedge Pre_B^f) \implies Post_B^f$
 - $(Post_A^g \wedge Pre_B^g) \implies Post_B^g$
- Asides:
 - Omitted requires/ensures stands for true
 - Anything \implies true

Is A a Behavioral Subtype of B?

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```
//@mathmodel M                                //@mathmodel M
//@constraint Inv_A                            //@constraint Inv_B
interface A {                                  interface B {

    //@requires Pre_A^f                        //@requires Pre_B^f
    //@ensures Post_A^f                       //@ensures Post_B^f
    int f(int x, int y);                       int f(int x, int y);

    //@requires Pre_A^g                        //@requires Pre_B^g
    //@alters this                             //@alters this
    //@ensures Post_A^g                       //@ensures Post_B^g
    void g(String s);                          void g(String s);
}                                              }
```

A is a Behavioral Subtype of B if...

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```

//@mathmodel MA      == //@mathmodel MB
//@constraint InvA   ==> //@constraint InvB
interface A {
    //@requires PrefA <== //@requires PrefB
    //@ensures PostfA ==> //@ensures PostfB
    int f(int x, int y);

    //@requires PregA <== //@requires PregB
    //@alters this      ==> //@alters this
    //@ensures PostgA ==> //@ensures PostgB
    void g(String s);
}
interface B {
    int f(int x, int y);

    void g(String s);
}

```

A is a Behavioral Subtype of B if...

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```

MA      == MB
InvA    ==> InvB
interface A {
    PrefA <== PrefB
    PostfA ^ PrefB ==> PostfB
    int f(int x, int y);

    PregA <== PregB
    this SubsetOf this
    PostgA ^ PregB ==> PostgB
    void g(String s);
}
interface B {
    int f(int x, int y);

    void g(String s);
}

```

Example: A is Behavioral Subtype of B

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```

//@mathmodel integer m    //@mathmodel integer m
//@cons m mod 10 = 0 ==> //@cons m is even
interface A {              interface B {

    //@req x*y >= 0         <==  //@req x = 0 or y = 0
    //@ens 10 < m < 100 ==>  //@ens 0 < m
    int f(int x, int y);    int f(int x, int y);

    void g(String s);       void g(String s);
}                             }

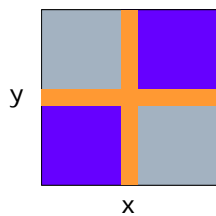
```

Visualization: Spec of f()

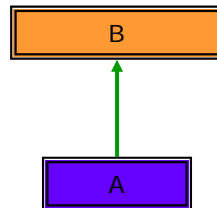
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Requires

$(x==0) \vee (y==0)$

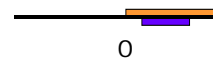


$x*y \ge 0$



Ensures

$0 < m$



$10 < m < 100$

Example: BigNatural & BigInteger

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- Should BigNatural extend BigInteger?
- For behavioral subtyping, ask:
 - Is BigNatural's invariant *stronger*?
 - Do all BigNatural methods *require less*?
 - Do all BigNatural methods *ensure more*?

BigNatural Extends BigInteger?

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```
//@mathmodel integer n    //@mathmodel integer n
//@constraint n >= 0      //@constraint
interface BigNatural {   interface BigInteger {

    //@alters n            //@alters n
    //@ens n = #n+1       //@ens n = #n+1
    void increment();     void increment();

    //@alters n            //@alters n
    //@ens n=max(0,#n-1)  //@ens n = #n-1
    void decrement();    void decrement();
}                          }
```

BigNatural Extends BigInteger?

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```
//@mathmodel integer n    //@mathmodel integer n
//@constraint n >= 0 ==>  //@constraint
interface BigNatural {   interface BigInteger {

    //@alters n            ==>    //@alters n
    //@ens n = #n+1       ==>    //@ens n = #n+1
    void increment();     void increment();

    //@alters n            ==>    //@alters n
    //@ens n=max(0,#n-1) ==>    //@ens n = #n-1
    void decrement();     void decrement();
}                          }
```

Example: BigNatural & BigInteger

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- Should BigNatural extend BigInteger?
- Is invariant stronger? **Yes!**
 - BigNatural invariant is $n \geq 0$
 - BigInteger invariant is true
- Do methods require less? **Yes!**
 - `increment()` requires the same (true) in both
 - `decrement()` requires the same (true) in both
- Do methods ensure more? **No!**
 - BigNatural `decrement()` ensures $n = \max(0, \#n-1)$
 - BigInteger `decrement()` ensures $n = \#n-1$
- Example client code that illustrates the problem

```
boolean alwaysTrue(BigInteger i) {
    String oldi = i.toString();
    i.decrement();
    i.increment();
    return (oldi.equals(i.toString()))
}
```

 - `alwaysTrue` is correct for BigInteger, not for BigNatural

Example: Square & Rectangle

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- These interfaces have similar abstract state (mathematical model)
 - two components: length, width
- These interfaces have similar public behavior (methods)
 - `getArea()`: returns the area (ie length * width)
 - `widthStretch()`: changes width of figure
 - `lengthStretch()`: changes length of figure
- Should we use inheritance?
 - Square extends Rectangle?
 - Rectangle extends Square?

Square Extends Rectangle?

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```
//@mathmodel l,w          //@mathmodel l,w
//@constraint l = w       //@constraint
interface Square {      interface Rectangle {

    //@ens getArea=l*w    //@ens getArea=l*w
    float getArea();     float getArea();

    //@alters l,w        //@alters w
    //@ens w = i*#w      //@ens w = i*#w
    // and l = i*#l      // and l = #l
    void widthStretch    void widthStretch
        (int i);         (int i);
}                          }
```

Square Extends Rectangle?

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```
//@mathmodel l,w          //@mathmodel l,w
//@constraint l = w ==>  //@constraint
interface Square {      interface Rectangle {

    //@ens getArea=l*w ==>  //@ens getArea=l*w
    float getArea();      float getArea();

    //@alters l,w          ==>  //@alters w
    //@ens w = i*#w        //@ens w = i*#w
    // and l = i*#l ==>  // and l = #l
    void widthStretch      void widthStretch
        (int i);          (int i);
}                          }
```

Example: Square is a Rectangle?

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- Is invariant stronger? **Yes!**
 - Square invariant is length = width and both are ≥ 0
 - Rectangle invariant is length and width both ≥ 0
- Do methods require less? **Yes!**
 - all methods require true in both classes
- Do methods ensure more? **No!**
 - Square widthStretch(s) ensures length = $i * \#length$
 - Rectangle widthStretch() ensures length = $\#length$
- Example client code that illustrates the problem

```
boolean alwaysTrue(Rectangle r) {
    double initialArea = r.getArea();
    double finalArea = r.widthStretch(2).getArea();
    return(finalArea == 2*initialArea);
}
```

 - alwaysTrue is correct for Rectangle, but not for Square

Rectangle Extends Square?

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```
//@mathmodel l,w          //@mathmodel l,w
//@constraint              //@constraint l = w
interface Rectangle {    interface Square {

    //@ens getArea=l*w    //@ens getArea=l*w
    float getArea();      float getArea();

    //@alters w           //@alters l,w
    //@ens w = i*#w      //@ens w = i*#w
    // and l = #l        // and l = i*#l
    void widthStretch    void widthStretch
        (int i);         (int i);
}                          }
```

Rectangle Extends Square?

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```
//@mathmodel l,w          //@mathmodel l,w
//@constraint              ==> //@constraint l = w
interface Rectangle {    interface Square {

    //@ens getArea=l*w ==> //@ens getArea=l*w
    float getArea();      float getArea();

    //@alters w           ==> //@alters l,w
    //@ens w = i*#w      //@ens w = i*#w
    // and l = #l        ==> // and l = i*#l
    void widthStretch    void widthStretch
        (int i);         (int i);
}                          }
```

Example: Rectangle is a Square?

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- Is invariant stronger? **No!**
 - Square invariant is length = width and both are ≥ 0
 - Rectangle invariant is length and width both > 0
- Do methods require less? **Yes!**
 - all methods require true in both classes
- Do methods ensure more? **No!**
 - Square widthStretch(s) ensures length = $i * \#length$
 - Rectangle widthStretch() ensures length = $\#length$
- Example client code that illustrates the problem

```
boolean alwaysTrue(Square s) {
    double initialArea = s.getArea();
    double finalArea = s.widthStretch(2).getArea();
    return(finalArea == 4*initialArea);
}
```

 - alwaysTrue is correct for Square, but not for Rectangle

Java Support for Subtyping

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- Java does not enforce behavioral contracts
 - Type checking ensures only that arguments match
- Support for behavioral subtyping limited to very weak promises, such as:
 - If B has a visible method $f()$, A has a visible method $f()$ with same signature
 - A can not *decrease* visibility of $f()$!
 - Arguments must match exactly (too much!)
 - Return type *can be* a subtype (covariance)
 - If B's method $f()$ can not throw an exception of type E, neither can A's $f()$
 - A can not *increase* the list of possible exceptions
 - We'll talk about exceptions later...

Summary

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- Interface extensions
 - Declaration syntax
 - Vocabulary: super/sub, base/derived, parent/child
 - Widening (up) is automatic
 - Narrowing (down) requires explicit cast
- Behavioral subtyping
 - Substitution principle
- Subtyping rules
 - Strengthen the constraint
 - Weaken the requires of each method
 - Strengthen the ensures of each method
- Java rules (syntax)
 - Does not allow contravariance of argument types
 - Does allow covariance of return type