Concepts of Object-Oriented Programming

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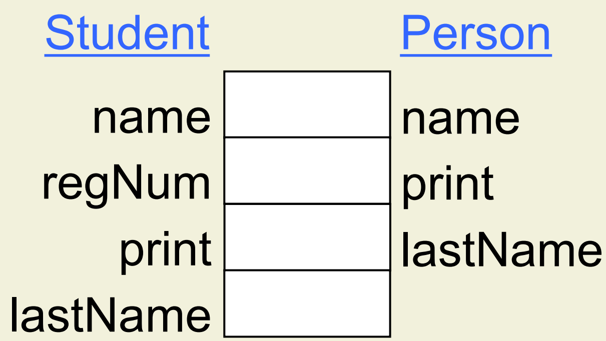
C-Example Revisited

```
struct sPerson {
  String name;
  void   ( *print )( Person* );
  String ( *lastName )( Person* );
};
```

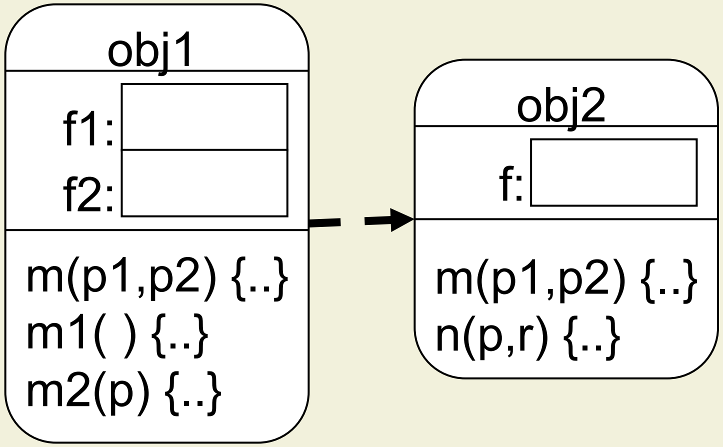
```
Student *s;
Person *p;
s = StudentC( “Susan Roberts“ );
p = (Person *) s;
p -> name = p -> lastName( p );
p -> print( p );
```

```
typedef struct sStudent Student;
struct sStudent {
  String name;
  int regNum;
  void   ( *print )( Student* );
  String ( *lastName )( Student* );
};
```



Message not Understood

- Objects access fields and methods of other objects
- A safe language detects situations where the receiver object does not have the accessed field or method
- Type systems can be used to detect such errors

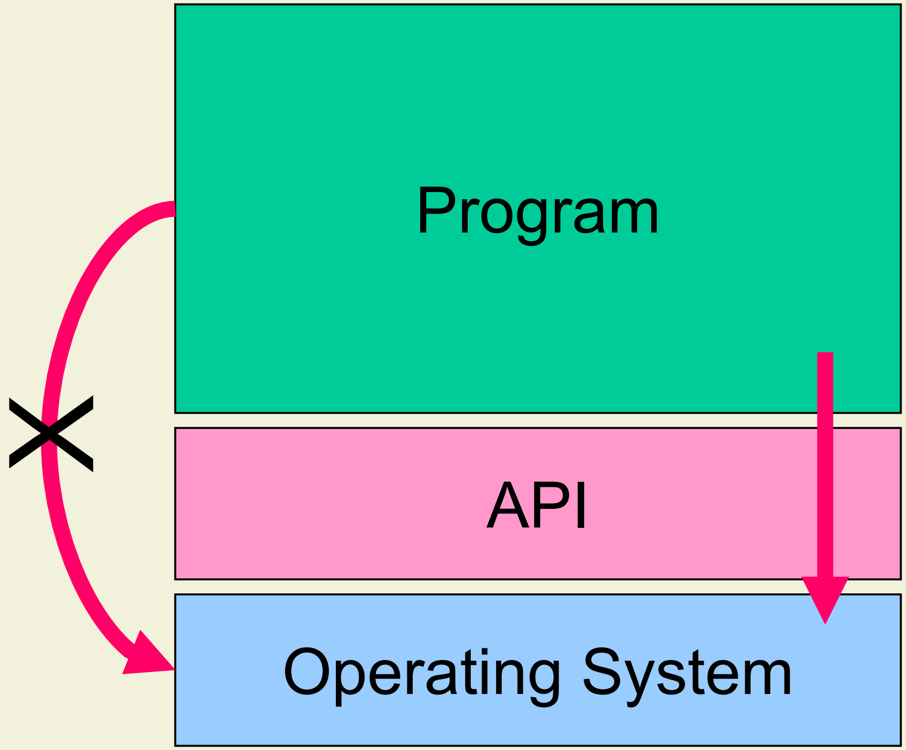



```
…
r = obj2.m( 0, 1 );
s = obj2.f;
```

```
r = obj2.m( );
r = obj2.anotherMethod( 0, 1 );
s = obj2.anotherField;
```

Java Security Model (Sandbox)

- Applets get access to system resources only through an API
- Access control can be implemented in API (security manager)
- Code must be prevented from by-passing API



2. Types and Subtyping

2.1 Types

2.2 Subtyping

2.3 Behavioral Subtyping

Type Systems

- Definition:
  A type system is a tractable syntactic method for proving absence of certain program behaviors by classifying phrases according to the kinds of values they compute.

  [B.C. Pierce, 2002]

- *Syntactic*: Rules are based on form, not behavior
- *Phrases*: Expressions, methods, etc. of a program
- *Kinds of values*: Types

Weak and Strong Type Systems

- Untyped languages
  - Do not classify values into types
  - Example: assembly languages
- Weakly-typed languages
  - Classify values into types, but do not strictly enforce additional restrictions
  - Example: C, C++
- Strongly-typed languages
  - Enforce that all operations are applied to arguments of the appropriate types
  - Examples: C#, Eiffel, Java, Python, Scala, Smalltalk

Weak vs. Strong Typing: Example

C

```
int main( int argc, char** argv ) {
  int i = ( int ) argv[ 0 ];
  printf( "%d", i );
}
```

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Java

```
int main( String[ ] argv ) {
  int i = ( int ) argv[ 0 ];
  System.out.println( i );
}
```

Compile-time error:

inconvertible types

found : java.lang.String

required: int

- Strongly-typed languages prevent certain erroneous or undesirable program behaviors

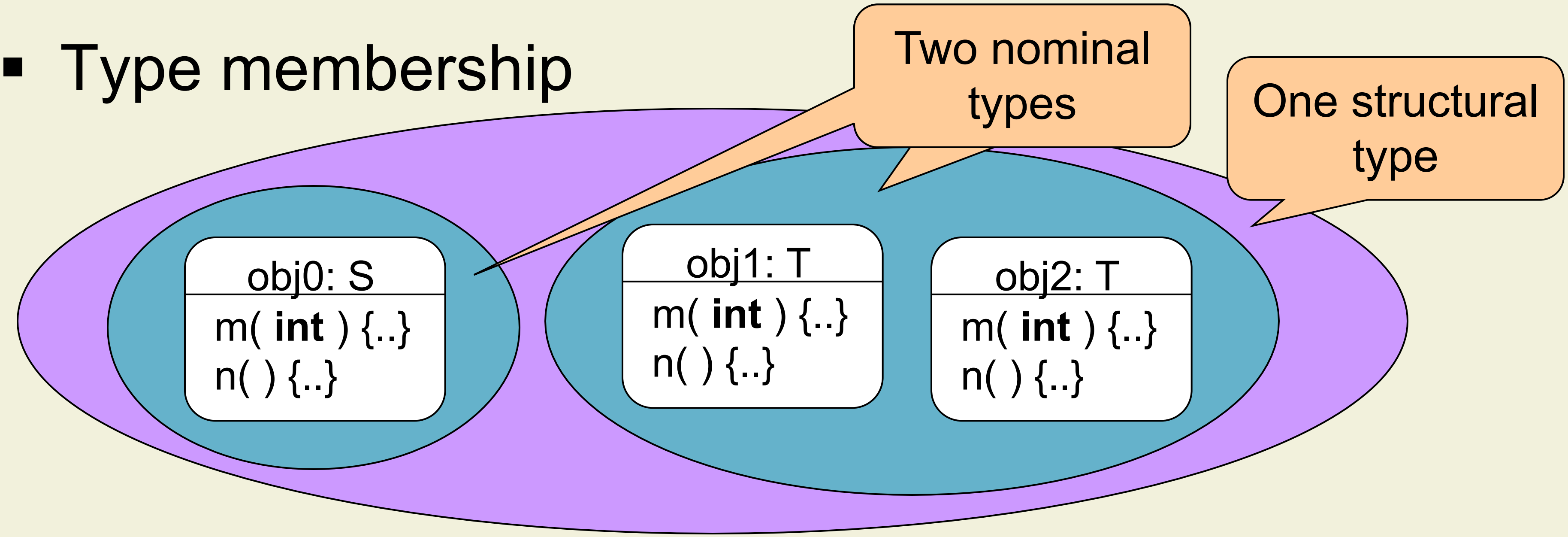
Types

- Definition:
  A type is a set of values sharing some properties.
  A value v has type T if v is an element of T.

- Question: what are the "*properties*" shared by the values of a type?
  - Nominal types:
    based on type names
    Examples: C++, Eiffel, Java, Scala
  - Structural types:
    based on availability of methods and fields
    Examples: Go, O'Caml, Python, Ruby, Smalltalk

Nominal and Structural Types

- Type membership



- Type equivalence
  - S and T are different in nominal systems
  - S and T are equivalent in structural systems

```
class S {
  m( int ) {…}
  n( ) {…}
}
```

```
class T {
  m( int ) {…}
  n( ) {…}
}
```

Static Type Checking

- Each expression of a program has a type
- Types of variables and methods are declared explicitly or inferred
- Types of expressions can be derived from the types of their constituents
- Type rules are used at compile time to check whether a program is correctly typed

Java
```
"A string"
5 + 7
```

Java
```
int a;
boolean equals( Object o )
```

Java
```
a + 7
"A number: " + 7
"A string".equals( null )
```

Java
```
a = "A string";
"A string".equals( 1, 2 )
```

Compile-time errors

DynamicType Checking

- Variables, methods, and expressions of a program are typically not typed
- Every object and value has a type
- Run-time system checks that operations are applied to expected arguments

Python
```
"A string"
5 + 7
```

Python
```
a = …;
def foo( o ): …
```

Python
```
a + 7
"A number: " * 7
foo( None )
```

Python
```
a = "A string"
a = 7
```

Python
```
a = "A string" / 5
foo( 5, 7 )
```

Run-time errors

Static Type Safety

- Definition:
  A programming language is called type-safe if its design prevents type errors.

- Statically type-safe object-oriented languages guarantee the following type invariant:
  In every execution state, the value held by variable v is an element of the declared type of v

- Type safety guarantees the absence of certain run-time errors

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Run-Time Checks in Static Type Systems

- Most static type systems rely on dynamic checks for certain operations
- Common example: type conversions by casts
- Run-time checks throw an exception in case of a type error

```
Object[ ] oa = new Object[ 10 ];
String s = "A String";

oa[ 0 ] = s;

…
if ( oa[ 0 ] instanceof String )
  s = (String) oa[ 0 ];

s = s.concat( "Another String" );
```

Expressiveness of Dynamic Type Systems

- Static checkers need to approximate run-time behavior (conservative checks)

Python

```
def divide( n, d ):
  if d != 0: res = n / d
  else: res = "Division by zero"
  print res
```

- Dynamic checkers support on-the-fly code generation and dynamic class loading

JavaScript

```
eval(
  "x=10; y=20; document.write( x*y )"
);
```

Bypassing Static Type Checks

- Some static type systems provide ways to bypass static checks
  - C#, Scala
  - Useful to interoperate with dynamically-typed languages or the HTML Document Object Model (DOM)

```
dynamic v = getPythonObject( );
dynamic res = v.Foo( 5 );
```

C#

Result is dynamic

Existence of method not checked at compile time

- Type safety is preserved via run-time checks

Static vs. Dynamic Type Checking

Advantages of static checking

- Static safety: More errors are found at compile time
- Readability: Types are excellent documentation
- Efficiency: Type information allows optimizations
- Tool support: Types enable auto-completion, support for refactoring, etc.

Advantages of dynamic checking

- Expressiveness: No correct program is rejected by the type checker
- Low overhead: No need to write type annotations
- Simplicity: Static type systems are often complicated

Type Systems in OO-Languages

	Static	Dynamic
Nominal	C++, C#, Eiffel, Java, Scala	
Structural	Go, OCaml	JavaScript, Python, Ruby, Smalltalk

"When I see a bird that walks like a duck and swims like a duck and quacks like a duck, I call that bird a duck."
[James Whitcomb Riley]

Often called "duck typing"

2. Types and Subtyping

Classification in Software Technology

- Substitution principle
  Objects of subtypes can be used wherever objects of supertypes are expected

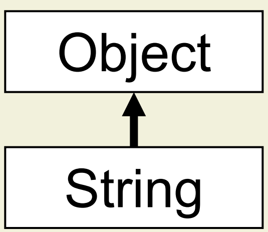
- Syntactic classification
  - Subtype objects can understand at least the messages that supertype objects can understand

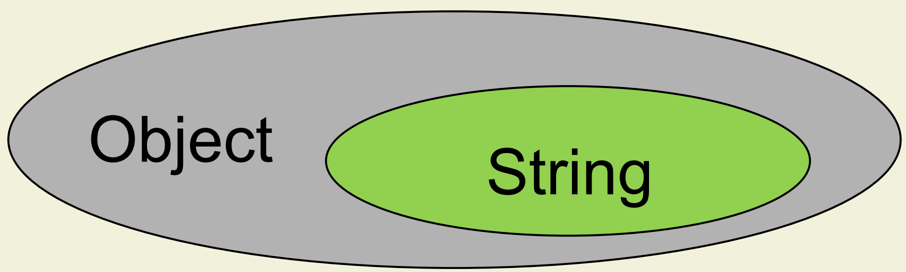
- Semantic classification
  - Subtype objects provide at least the behavior of supertype objects

Subtyping

- Definition of “Type”:
  A type is a set of values sharing some properties. A value v has type T if v is an element of T.

- The subtype relation corresponds to the subset relation on the values of a type





Nominal and Structural Subtyping

- Nominal type systems
  - Determine type membership based on type names
  - Determine subtype relations based on explicit declarations
- Structural type systems
  - Determine type membership and subtype relations based on availability of methods and fields

```
class S { m( int ) {…} }
```

```
class T
extends S {
  m( int ) {…}
}
```

```
class U {
  m( int ) {…}
  n( ) {…}
}
```

Only T is a nominal subtype of S

```
class T {
  m( int ) {…}
}
```

```
class U {
  m( int ) {…}
  n( ) {…}
}
```

T's and U's type are structural subtypes of S's type

Nominal Subtyping and Substitution

- Subtype objects can understand at least the messages that supertype objects can understand
  - Method calls
  - Field accesses

- Subtype objects have wider interfaces than supertype objects
  - Existence of methods and fields
  - Accessibility of methods and fields
  - Types of methods and fields

Existence

```
class Super {
  void foo( ) { … }
  void bar( ) { … }
}

class Sub <: Super {
  void foo( ) { … }
  // no bar( )
}
```

```
void m( Super s ) { s.bar( ); }
```

- Sub narrows Super’s interface
- If m is called with a Sub object as parameter, execution fails
- Subtypes may add, but not remove methods and fields

Accessibility

```
class Super {
  public void foo( ) { … }
  public void bar( ) { … }
}
class Sub <: Super {
  public void foo( ) { … }
  private void bar( ) { … }
}
```

```
void m( Super s ) { s.bar( ); }
```

- At run time, m could access a private method of Sub, thereby violating information hiding
- An overriding method must not be less accessible than the methods it overrides

Overriding: Parameter Types

```
class Super {
  void foo( String s ) { … }
  void bar( Object o ) { … }
}

class Sub <: Super {
  void foo( Object s ) { … }
  void bar( String o ) { … }
}
```

```
void m( Super s ) {
  s.foo( "Hello" );
  s.bar( new Object( ) );
}
```

- Calling m with a Sub object demonstrates a violation of static type safety
  - o in Sub.bar is not a String
- Contravariant parameters: An overriding method must not require more specific parameter types than the methods it overrides

Overriding: Result Types

```
class Super {
  Object foo( ) { … }
  String bar( ) { … }
}

class Sub <: Super {
 String foo( ) { … }
 Object bar( ) { … }
}
```

```
void m( Super s ) {
  Object o = s.foo( );
  String t = s.bar( );
}
```

- Calling m with a Sub object demonstrates a violation of static type safety
  - t in m is not a String
- Covariant results:
  An overriding method must not have a more general result type than the methods it overrides
  - Out-parameters and exceptions are results

Overriding: Fields

```
class Super {
  Object f;
  String g;
}

class Sub <: Super {
 String f;
 Object g;
}
```

```
void m( Super s ) {
  s.f = new Object( );
  String t = s.g;
}
```

- Calling m with a Sub object demonstrates a violation of static type safety
  - s.f is not a String
  - t is not a String
- Subtypes must not change the types of fields
  - Fields are bound statically

Overriding: Fields (cont'd)

```
class Super {
  T f;
  void setF( T f ) { this.f = f; }
  T getF( ) { return f; }
}

class Sub <: Super {
  S f;
  void setF( S f ) { this.f = f; }
  S getF( ) { return f; }
}
```

- Regard field as pair of getter and setter methods
  - Specializing a field type (S <: T) corresponds to specializing the argument of the setter (violates contravariant parameters)
  - Generalizing a field type (T <: S) corresponds to generalizing the result of the getter (violates covariant results)

Overriding: Immutable Fields

class Super {
  final T f;
  ~~**void** setF(T f) { **this**.f = f; }~~
  T getF( ) { **return** f; }
}

class Sub <: Super {
  final S f;
  ~~**void** setF(S f) { **this**.f = f; }~~
  S getF( ) { **return** f; }
}

- Immutable fields do not have setters
- Types of immutable fields can be specialized in subclasses (S <: T)
  - Works only if the supertype constructor does not initialize f for subtype objects (with a T-value)!
- Not permitted by mainstream languages

Narrowing Interfaces in Eiffel

- Eiffel permits the “illegal” narrowing of interfaces
  - Changing the existence of methods
  - Overriding with covariant parameter types
  - Specializing field types
- Run-time exception “*catcall detected for argument #1 'o' expected STRING but got ANY*“

```
class SUPER
feature
  bar ( o: ANY ) do … end
end

class SUB inherit SUPER
redefine bar end
feature
  bar ( o: STRING ) do … end
end
```

```
m ( s: SUPER )
do
  s.bar ( create {ANY} )
end
```

Narrowing Interfaces in Eiffel (cont'd)

- With attached (non-null) types, covariant overriding requires a detachable (possibly-null) type
- Run-time system passes null when an argument is not of the expected type
- Method must check for null-ness explicitly

```
class SUPER
feature
  bar ( o: ANY ) do … end
end

class SUB inherit SUPER
redefine bar end
feature
  bar ( o: ?STRING )
  do
    if attached o then o.foo;
    else … end
  end
end
```

Covariant Arrays

```
class C {
  void foo( Object[ ] a ) {
    if( a.length > 0 )
      a[ 0 ] = new Object( );
  }
}
```

```
void client( C c ) {
  c.foo( new String[ 5 ] );
}
```

- In Java and C#, arrays are covariant
  - If S <: T then S[ ] <: T[ ]

```
class Object[ ] {

  public Object 0;
  public Object 1;
  …
}
```

```
class String[ ]
      <: Object[ ] {
  public String 0;
  public String 1;
  …
}
```

- Each array update requires a run-time type check

Covariant Arrays (cont'd)

- Covariant arrays allow one to write methods that work for all arrays such as

```
class Arrays {
  public static void fill( Object[ ] a, Object val ) { … }
}
```

- Here, the designers of Java and C# resolved the trade-off between expressiveness and static safety in favor of expressiveness
- Generics allow a solution that is expressive and statically safe (more later)

Shortcomings of Nominal Subtyping (1)

- Nominal subtyping can impede reuse
- Consider two library classes

```
class Resident {
  String getName( ) { … }
  Data dateOfBirth( ) { … }
  Address getAddress( ) { … }
}
```

```
class Employee {
  String getName( ) { … }
  Data dateOfBirth( ) { … }
  int getSalary( ) { … }
}
```

- Now we would like to store Resident and Employee-objects in a collection of type Person[ ]
  - Neither Resident nor Employee is a subtype of Person

Reuse: Adapter Pattern

- Implement Adapter (wrapper)
  - Subtype of Person
  - Delegate calls to adaptee (Resident or Employee)

```
interface Person {
  String getName( );
  Data dateOfBirth( );
}
```

```
class EmployeeAdapter implements Person {
  private Employee adaptee;
  String getName( ) { return adaptee.getName( ); }
  Data dateOfBirth() { return adaptee.dateOfBirth( ); }
}
```

- Adapter requires boilerplate code
- Adapter causes memory and run-time overhead
- Works also if Person is reused

Reuse: Generalization

- Most OO-languages support specialization of superclasses (top-down development)
- Some research languages (e.g., Sather, Cecil) also support generalization (bottom-up development)

```
interface Person generalizes Resident, Employee {
  String getName( );
  Data dateOfBirth( );
}
```

- Supertype can be declared after subtype has been implemented

Reuse: Generalization (cont'd)

- Generalization does not imply inheritance
- Subclass-to-be already has a superclass
  - Single inheritance: exchanging the superclass might affect the subclass
  - Multiple inheritance: additional superclass may cause conflicts

```
class Cell {
  int value;
  int getData( ) { return value; }
}
```

```
abstract class DataPoint
                    generalizes Cell {
  abstract int getData( );
  boolean equals( Object o ) {
    … // check type of o
    return getData( ) ==
              ( (DataPoint) o ).getData( );
  }
}
```

Shortcomings of Nominal Subtyping (2)

- Nominal subtyping can limit generality
- Many method signatures are overly restrictive

```
void printData( Collection<String> c ) {
  if( c.isEmpty() ) System.out.println( "empty" );
  else {
    Iterator<String> iter = c.iterator( );
    while( iter.hasNext() ) System.out.println( iter.next() );
  }
}
```

- printData uses only two methods of c, but requires a type with 13 methods

Generality: Additional Supertypes

- Make type requirements weaker by declaring interfaces for useful supertypes
- But: many useful subsets of operations
  - Read-only collection
  - Write-only collection (log file)
  - Convertible collection
  - Combinations of the above
- Overhead for declaring supertypes and subtyping

```
interface Iterable<E> {
  Iterator<E> iterator( );
}
```

```
interface Collection<E>
          extends Iterable<E> {
  // 13 methods
}
```

Generality: Optional Methods

- Java documentation marks some methods as “optional”
  - Implementation is allowed to throw an unchecked exception
  - For Collection: all mutating methods
- Static safety is lost

```
interface Collection<E>
                    extends Iterable<E> {
  /* 13 methods, out of which 6 are
      optional */
}
```

```
class AbstractCollection<E>
          implements Collection<E> {
  boolean add( E e ) {
    throw new
      UnsupportedOperationException( );
  }
  …
}
```

Structural Subtyping and Substitution

- Subtype objects can understand at least the messages that supertype objects can understand
  - Method calls
  - Field accesses
- Structural subtypes have by definition wider interfaces than their supertypes

Reuse: Structural Subtyping

- All types are "automatically" subtypes of types with smaller interfaces
  - No extra code or declarations required
- Subtyping does not imply inheritance (like generalization)
- Person is a supertype of Resident and Employee

```
interface Person {
  String getName( );
  Data dateOfBirth( );
}
```

```
class Resident {
  String getName( ) { … }
  Data dateOfBirth( ) { … }
  … }
```

```
class Employee {
  String getName( ) { … }
  Data dateOfBirth( ) { … }
  … }
```

Generality: Structural Subtyping

```
void printData( Collection<String> c ) {
  // uses only c.isEmpty() and c.iterator()
}
```

- Static type checking
  - Additional-supertypes approach applies
  - Additional supertypes must be declared, but not the subtype relation
- Dynamic type checking
  - Arguments to operations are not restricted
  - Similar to optional-methods approach (possible run-time error)

Type Systems in OO-Languages

	Static	Dynamic
Nominal	Sweetspot: Maximum static safety	Why should one declare all the type information but then not check it statically?
Structural	Overhead of declaring many types is inconvenient; Problems with semantics of subtypes (see later)	Sweetspot: Maximum flexibility

2. Types and Subtyping

Types

- Definition:
  A type is a set of values sharing some properties.
  A value v has type T if v is an element of T.

- Question: what are the "*properties*" shared by the values of a type?
  - So far we focused on syntax

- "*Properties*" should also include the behavior of the object
  - Expressed as interface specifications (contracts)

Method Behavior

- Preconditions have to hold in the state before the method body is executed
- Postconditions have to hold in the state after the method body has terminated
- Old-expressions can be used to refer to prestate values from the postcondition

```
class BoundedList {
  Object[ ] elems;
  int free;  // next free slot
  …
  // requires free < elems.length
  // ensures elems[ old( free ) ] == e
  void add( Object e )  { … }
}
```

Object Invariants

- Object invariants describe consistency criteria for objects
- Invariants have to hold in all states, in which an object can be accessed by other objects

```
class BoundedList {
  Object[ ] elems;
  int free;  // next free slot
  /* invariant
      elems != null              &&
      0 <= free                  &&
      free <= elems.length        */
  …
  // requires free < elems.length
  // ensures elems[ old( free ) ] == e
  void add( Object e )  { … }
}
```

Visible States

- Invariants have to hold in pre- and poststates of methods executions but may be violated temporarily in between
- Pre- and poststates are called "visible states"

```
class Redundant {
  private int a, b;
  // invariant a == b

  public void set( int v ) {
    // invariant of this holds
    a = v;
    // invariant of this violated
    b = v;
    // invariant of this holds
  }
}
```

History Constraints

- History constraints describe how objects evolve over time
- History constraints relate visible states
- Constraints must be reflexive and transitive

```
class Person {
  int age;

  // constraint old( age ) <= age

  Person( int age ) {
    this.age = age;
  }

  …
}
```

```
Person p = new Person( 7 );
…
…
assert 7 <= p.age;
```

Static vs. Dynamic Contract Checking

Static checking

Program verification

- Static safety: More errors are found at compile time
- Complexity: Static contract checking is difficult and not yet mainstream
- Large overhead: Static contract checking requires extensive contracts
- Examples: Spec#, .NET

Dynamic checking

Run-time assertion checking

- Incompleteness: Not all properties can be checked (efficiently) at run time
- Efficient bug-finding: Complements testing
- Low overhead: Partial contracts are useful
- Examples: Eiffel, .NET

Contracts and Subtyping

```
class Number {

  int n;
  // invariant true

  // requires true
  // ensures n == p
  void set( int  p )
      { n = p; }
  …
}
```

```
class UndoNaturalNumber
                              extends Number {
  int undo;
  // invariant 0 < n && 0 < undo

  // requires 0 < p
  // ensures n == p && undo == old( n )
  void set( int  p )
      { undo = n; n = p; }
  …
}
```

- Subtypes specialize the behavior of supertypes
- What are legal specializations?

Rules for Subtyping: Preconditions

```
class Super {
  // requires 0 <= n && n < 5
  void foo( int n ) {
    char[ ] tmp = new char[ 5 ];
    tmp[ n ] = 'X';
  }
}
```

```
class Sub extends Super {
  // requires 0 <= n && n < 3
  void foo( int n ) {
    char[ ] tmp = new char[ 3 ];
    tmp[ n ] = 'X';
  }
}
```

```
void crash( Super s ) {
  s.foo( 4 );
}
```

```
x.crash( new Sub( ) );
```

- Subtype objects must fulfill contracts of supertypes
- Overriding methods of subtypes may have weaker preconditions than corresponding supertype methods

Rules for Subtyping: Postconditions

```
class Super {
  // ensures 0 < result
  int foo( ) {
    return 1;
  }
}
```

```
class Sub extends Super {
  // ensures 0 <= result
  int foo( ) {
    return 0;
  }
}
```

```
void crash( Super s ) {
  int i = 5 / s.foo( );
}
```

```
x.crash( new Sub( ) );
```

- Overriding methods of subtypes may have stronger postconditions than corresponding supertype methods

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Rules for Subtyping: Invariants

```
class Super {
  int n;
  // invariant 0 < n
  Super( )      { n = 5; }
  int crash( )  { return 5 / n; }
}
```

```
new Sub( ).crash( );
```

```
class Sub extends Super {
 // invariant 0 <= n
  Sub( ) {
    n = 0;
  }
}
```

- Subtypes may have stronger invariants

Rules for Subtyping: History Constraints

```
class Super {
  int n;

  // constraint old( n ) <= n

  int get( ) { return n; }

  void foo( ) { }
}
```

```
class Sub extends Super {
  // constraint true

  void foo( ) {
    n = n – 1;
  }
}
```

```
int crash( Super s ) {
  int cache = s.get( ) – 1;
  s.foo( );
  return 5 / ( cache – s.get() );
}
```

```
x.crash( new Sub( ) );
```

- Subtypes may have stronger history constraints

Natural Numbers Revisited

```
class Number {

  int n;
  // invariant true

  // requires true
  // ensures n == p
  void set( int  p )
      { n = p; }
  …
}
```

```
class UndoNaturalNumber
                  extends Number {
  int undo;
  // invariant 0 < n && 0 < undo

  // requires 0 < p
  // ensures n == p && undo == old( n )
  void set( int  p )
      { undo = n; n = p; }
  …
}
```

- UndoNaturalNumber does not specialize the behavior of Number

Rules for Subtyping: Summary

- Subtype objects must fulfill contracts of supertypes, but:
  - Subtypes can have stronger invariants
  - Subtypes can have stronger history constraints
  - Overriding methods of subtypes can have
    weaker preconditions
    stronger postconditions
    than corresponding supertype methods

- Concept is called Behavioral Subtyping

Static Checking of Behavioral Subtyping

- For each override S.m of T.m check for all parameters, heaps, and results:
  - $Pre_{T.m} \Rightarrow Pre_{S.m}$
  - $Post_{S.m} \Rightarrow Post_{T.m}$

- The above rule for postconditions is sound, but overly restrictive

```
class Super {
  // requires 0 < p
  // ensures 0 < result
  int foo( int p ) { … }          }
```

```
class Sub extends Super {
  // requires true
  // ensures p < result
  int foo( int p ) { … }          }
```

```
int client( Super s ) {
  int r = s.foo( 5 );
  assert 0 < r;
}
```

Improved Postcondition Rule

- Any caller that wants to use the supertype postcondition must establish the supertype precondition
- Improved rule (attempt):
  For each override S.m of T.m check for all parameters, heaps, and results:
  - $Pre_{T.m} \Rightarrow Pre_{S.m}$
  - $Pre_{T.m} \Rightarrow (Post_{S.m} \Rightarrow Post_{T.m})$

```
class Super {
  // requires 0 < p
  // ensures 0 < result
  int foo( int p ) { … }        }
```

```
class Sub extends Super {
  // requires true
  // ensures p < result
  int foo( int p ) { … }        }
```

```
int client( Super s ) {
  int r = s.foo( 5 );
  assert 0 < r;
}
```

Improved Postcondition Rule (c't)

- Any caller that wants to use the supertype postcondition must establish the supertype precondition
- Improved rule (definite):
  For each override S.m of T.m check for all parameters, heaps, and results:
  - $Pre_{T.m} \Rightarrow Pre_{S.m}$
  - $old(Pre_{T.m}) \Rightarrow (Post_{S.m} \Rightarrow Post_{T.m})$

```
class Super {
  int p;
  // requires 0 < p
  // ensures 0 < result
  int foo( ) { … }          }
```

```
class Sub extends Super {
  // requires true
  // ensures p < result
  int foo( )
  { p = -2; return -1; }
}
```

```
int client( Super s ) {
  s.p = 5;  int r = s.foo( );
  assert 0 < r;
}
```

Static Checking of Behav. Subtyping (c't)

- Assume contracts are actually part of the program
- For each subtype S <: T check for all heaps:
  - Inv_S => Inv_T
  - $Cons_S$ => $Cons_T$
- But: entailment is undecidable

```
class Super {
  // requires p == p*p
  // ensures p < result
  int foo( int p ) { … }          }
```

```
class Sub extends Super {
  // requires p == 0 || p == 1
  // ensures result == 2
  int foo( int p ) { … }          }
```

  - For all p :: p == p*p => (p == 0 || p == 1)
  - For all p, result ::
    old(p == p*p) => (result == 2 => p < result)

Specification Inheritance

- Behavioral subtyping can be enforced by inheriting specifications from supertypes
- Rule for invariants
  - The effective invariant of a type S is the conjunction of the invariant declared in S and the invariants declared in the supertypes of S
  - Subtypes have stronger effective invariants
  - Analogous for history constraints

```
class Super {
  int n;
  // invariant 0 < n
  Super( ) { n = 5; }
  int crash( ) {
    return 5 / n;
  }
}
```

```
class Sub extends Super {
  // invariant 0 <= n
  Sub( ) { n = 0; }
}
```

Violates inherited invariant

Simple Inheritance of Method Contracts

- An overriding method must not declare additional preconditions
  - The overriding and the overridden method have identical preconditions

```
class Super {
  // requires 0 <= n && n < 5
  void foo( int n ) { … }
}
```

```
class Sub extends Super {
  // requires 0 <= n && n < 3
  void foo( int n ) { … }
}
```

- The postcondition of an overriding method is the conjunction of the postcondition declared for the method and the postconditions declared for the methods it overrides
  - Overriding methods have stronger postconditions

Precondition Inheritance: Shortcomings

- Simple rule does not work for multiple subtyping

```
interface I {
  // requires 0 < n
  int foo( int n );
}
```

```
interface J {
  // requires n < 0
  int foo( int n );
}
```

```
class C implements I, J {
  int foo( int n ) { … }
}
```

What is the resulting precondition?

- Simple rule does not allow precondition weakening

```
class Set {
  // requires contains( x )
  void remove( Object x )
  { … }
}
```

```
class MySet extends Set {
  // requires true
  void remove( Object x )
  { … }
}
```

Precondition Inheritance: Improved Rule

```
interface I {
  // requires 0 < n
  // ensures result == n
  int foo( int n );
}
```

```
interface J {
  // requires n < 0
  // ensures result == –n
  int foo( int n );
}
```

```
class C implements I, J {
  int foo( int n ) { … }
}
```

- Clients view an object through a static type

```
void client1( I x ) {
  // assert 0 < 5
  int y = x.foo( 5 )
  // assume y == 5
}
```

```
void client2( J x ) {
  // assert -3 < 0
  int y = x.foo( -3 )
  // assume y == 3
}
```

- Idea: method implementation may assume only the disjunction of all inherited and declared preconditions

Effective Preconditions

- Let $Pre_{T.m}$ denote the precondition of method m declared in class T
- The effective precondition $PreEff_{S.m}$ of a method m in class S is the disjunction of the precondition $Pre_{S.m}$ declared for the method and the preconditions $Pre_{T.m}$ declared for the methods it overrides
  - $PreEff_{S.m} = Pre_{S.m} \,||\, Pre_{T.m} \,||\, Pre_{T'.m} \,||\, \ldots$
- Overriding methods have weaker eff. preconditions

Shortcomings Revisited

- Improved rule works for multiple subtyping

```
interface I {
  // requires 0 < n
  int foo( int n );
}
```

```
interface J {
  // requires n < 0
  int foo( int n );
}
```

```
class C implements I, J {
  int foo( int n ) { … }
}
```

Effective precondition: 0 < n || n < 0

- Improved rule allows precondition weakening

```
class Set {
  // requires contains( x )
  void remove( Object x )
  { … }
}
```

```
class MySet extends Set {
  // requires true
  void remove( Object x )
  { … }
}
```

Effective precondition: contains(x) || true

Postcondition Inheritance: Improved Rule

- Simple postcondition rule becomes too restrictive

```
class Set {
  // requires contains( x )
  // ensures size() == old( size() – 1 )
  void remove( Object x )
  { … }
}
```

```
class MySet extends Set {
  // requires true
  void remove( Object x )
  { … }
}
```

- Idea: method implementation needs to satisfy each postcondition for which the corresponding precondition holds
  - $PostEff_{S.m} = (Pre_{S.m} \Rightarrow Post_{S.m})\ \&\&\ (Pre_{T.m} \Rightarrow Post_{T.m})\ \ldots$

Postcondition Inheritance: Improved Rule

```
class Set {
  // requires contains( x )
  // ensures !contains( x )
  void remove( Object x )
  { … }
}
```

```
class MySet extends Set {
  // requires true
  // ensures true
  void remove( Object x )
  { … }
}
```

- Rule from previous slide produces a bogus result:
  - $PostEff_{MySet.remove}$ = (contains(x) => !contains(x)) && (true => true)
- Precondition must be evaluated in prestate:
  - $PostEff_{MySet.remove}$ = (old(contains(x)) => !contains(x)) && (old(true) => true)

Effective Postconditions

- Let $Post_{T.m}$ denote the postcondition of method m declared in class T
- The effective postcondition $PostEff_{S.m}$ of a method m in class S is the conjunction of implications $(old(Pre_{T.m}) \Rightarrow Post_{T.m})$ for all types T such that T declares S.m or S.m overrides T.m
  - $PostEff_{S.m} = (old(Pre_{S.m}) \Rightarrow Post_{S.m})\ \&\&$
    $(old(Pre_{T.m}) \Rightarrow Post_{T.m})\ \&\&$
    $(old(Pre_{T'.m}) \Rightarrow Post_{T'.m})\ \&\&\ \ldots$
- Overriding methods have stronger effective postconditions

Beh. Subtyping and Spec. Inheritance

- Without specification inheritance, programmers need to ensure behavioral subtyping by checking that contracts obey the rules

- Specification inheritance is a language construct that automatically enforces behavioral subtyping by interpreting contracts such that they obey the rules
  - Subclasses have stronger effective invariants and history constraints
  - Overriding methods have weaker effective preconditions and stronger effective postconditions

Run-Time Checking

- Checking entailment for all arguments, heaps, and results is not possible at run time
  - For all p :: p == p*p => (p == 0 || p == 1)
- Specification inheritance avoids this problem by defining effective contracts, which satisfy behavioral subtyping
- The run-time checker can check effective contracts

Behavioral Structural Subtyping

- With dynamic type checking, callers have no static knowledge of contracts
  - Cannot establish precondition
  - Have no postcondition to assume
- Called method may check its own contract at run time
  - Precondition failures are analogous to “message not understood”; caller cannot be blamed
  - Postcondition failures may reveal error in method implementation (like an assert)

```
class Circle {
  draw( ) { … }
}
```

```
render( p ) {
  p.draw( );
}
```

```
class Cowboy {
  draw( ) { … }
}
```

Behavioral Structural Subtyping (cont'd)

- With static structural type checking, callers could state which signature and behavior they require

```
render( { void draw( )
          requires P
          ensures Q }  p ) {
  p.draw( );
}
```

Behavioral Structural Subtyping (cont'd)

```
class Circle {
  // requires P'
  // ensures Q'
  draw( ) { … }
}
```

```
render( { void draw( )
              requires P
              ensures Q }   p ) {
  p.draw( );
}
```

```
foo( ) { render( new Circle() ); }
```

- Behavioral subtyping needs to be checked when the type system determines a subtype relation
  - Static checking is possible, but not automatic
  - Dynamic checking is not possible (see above)
    - Caller cannot be blamed for violations of P'
    - Callee cannot be blamed for violations of Q
- Structural typing and behavioral subtyping do not integrate well

Types as Contracts

- Types can be seen as a special form of contract, where static checking is decidable

- Operator type(x) yields the type of the object stored in x
  - The dynamic type of x

```
class Types {
  Person p;

  String foo( Person q ) { … }
  …
}
```

```
class Types {
  p;
  // invariant type( p ) <: Person

  // requires type( q ) <: Person
  // ensures type( result ) <: String
  foo( q ) { … }
  …
}
```

Types as Contracts: Subtyping

```
class Super {
  S p;
  // invariant type( p ) <: S
  // requires type( q ) <: T
  // ensures type( result ) <: U
  U foo( T q ) { … }
}
```

```
class Sub <: Super {
  S' p;
  // invariant type( p ) <: S'
  // requires type( q ) <: T'
  // ensures type( result ) <: U'
  U' foo( T' q ) { … }
}
```

- Stronger invariant:
  - type(p) <: S' => type(p) <: S
    requires S' <: S — Covariance
- Weaker precondition
  - type(q) <: T => type(q) <: T'
    requires T <: T' — Contravariance
- Stronger postcondition:
  - type(result) <: U' =>
    type(result) <: U
    requires U' <: U — Covariance

Invariants over Inherited Fields

```
package Library;
public class Super {
  protected int f;
}
```

```
package Client;
public class Sub
                 extends Super {
  // invariant 0 <= f
}
```

```
package Library;
class Friend {
  void foo( Super s ) { s.f = –1; }
}
```

- Invariants over inherited field f can be violated by all methods that have access to f
- Static checking of such invariants is not modular
- Even without qualified field accesses (x.f = e), one needs to re-check all inherited methods

Immutable Types

- Objects of immutable types do not change their state after construction
- Advantages
  - No unexpected modifications of shared objects
  - No thread synchronization necessary
  - No inconsistent states
- Examples from Java
  - String, Integer

```
class ImmutableCell {
  private int value;

  ImmutableCell( int value ) {
    this.value = value;
  }

  int get( ) {
    return value;
  }

  // no setter
}
```

Immutable and Mutable Types

```
class ImmutableCell {
  int value;
  ImmutableCell( int value ) { … }
  int get( ) { … }
  // no setter
}
```

```
class Cell {
  int value;
  Cell( int value ) { … }
  int get( ) { … }
  void set( int value ) { … }
}
```

- What should be the subtype relation between mutable and immutable types?

Immutable and Mutable Types (cont'd)

```
class ImmutableCell extends Cell {
  ImmutableCell( int value ) { … }
  void set( int value ) {
    // throw exception
   }
}
```

```
class Cell {
  int value;
  Cell( int value ) { … }
  int get( ) { … }
  void set( int value ) { … }
}
```

- Proposal 1: Immutable type should be subtype
- Not possible because mutable type has wider interface

Immutable and Mutable Types (cont'd)

```
class ImmutableCell {
  int value;
  // constraint old( value ) == value
  … // no setter
}
```

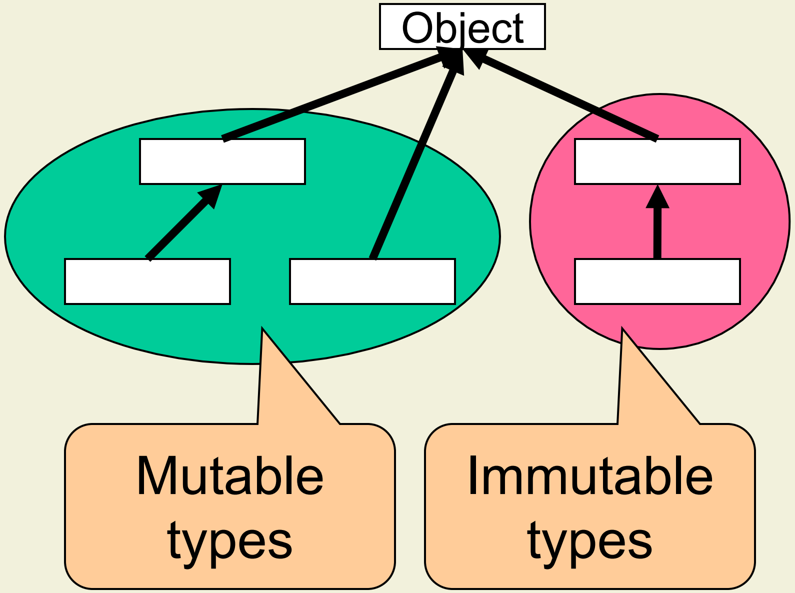
```
class Cell extends ImmutableCell {
  Cell( int value ) { … }
  void set( int value ) { … }
}
```

```
foo( ImmutableCell c ) {
  int cache = c.get( );
  …
  assert cache == c.get( );
}
```

- Proposal 2: Mutable type should be subtype
- Mutable type has wider interface
  - Also complies with structural subtyping
- But: Mutable type does not specialize behavior

Immutable and Mutable Types: Solutions

- Clean solution
  - No subtype relation between mutable and immutable types
  - Only exception: Object, which has no history constraint
- Java API contains immutable types that are subtypes of mutable types
  - AbstractCollection and Iterator are mutable
  - All mutating methods are optional



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