Concepts of Object-Oriented Programming

Peter Müller

Programming Methodology Group

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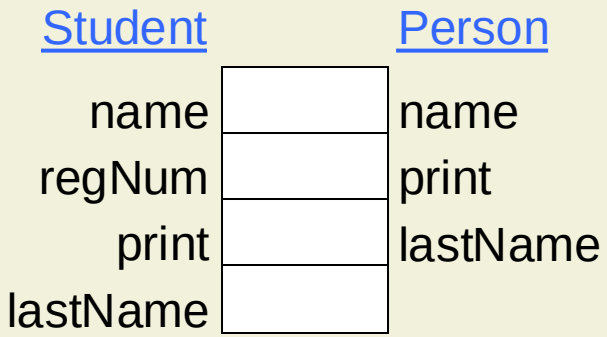
ETH zürich

C-Example Revisited

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

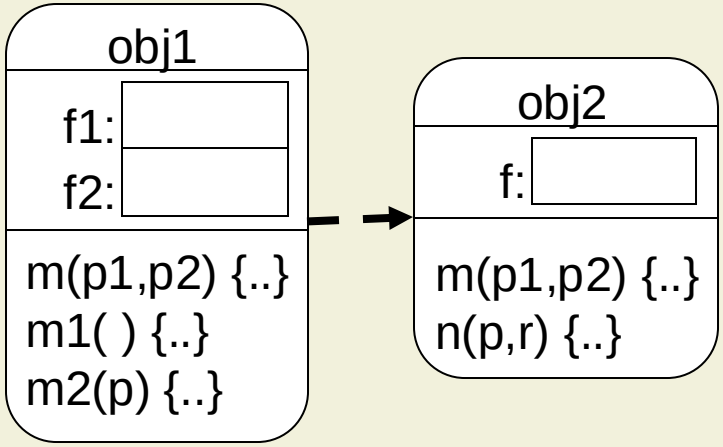
```
Student *s;
Person *p;
s = StudentC( "Susan Roberts" );
p = (Person *) s;
p -> name = p -> lastName( p );
p -> print( p );
```

```
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

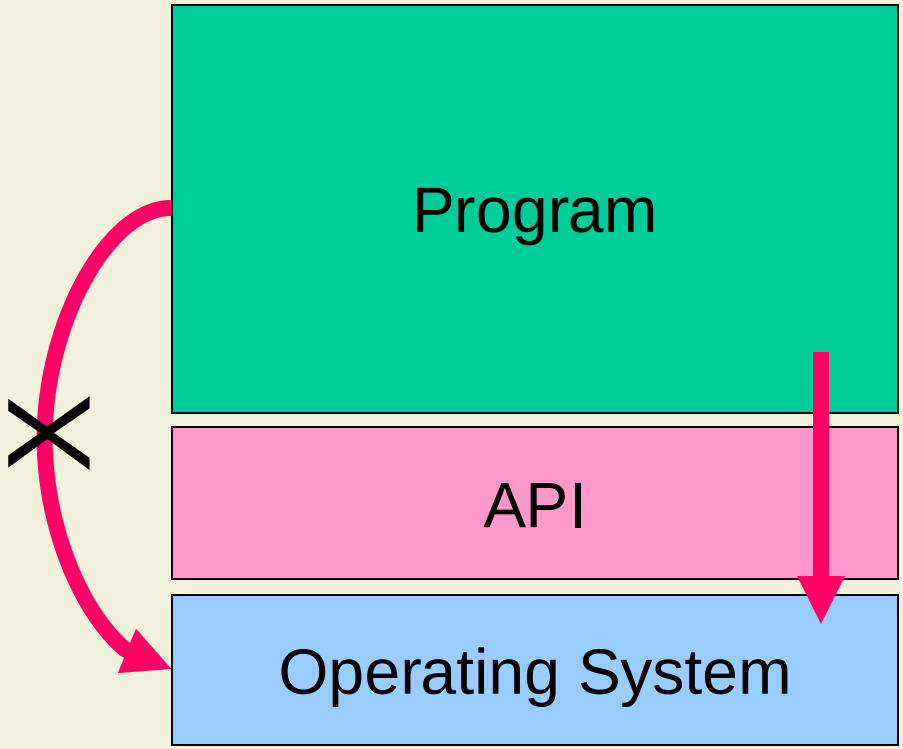



```
…
r = obj2.m( 0, 1 );
s = obj2.f;
```

```
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

Type Systems

- Definition:
  A type system is a tractable syntactic method for proving the 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

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

C

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

Java

```
1628878672
```

Compile-time error:

```
inconvertible types
found    : java.lang.String
required: int
```

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

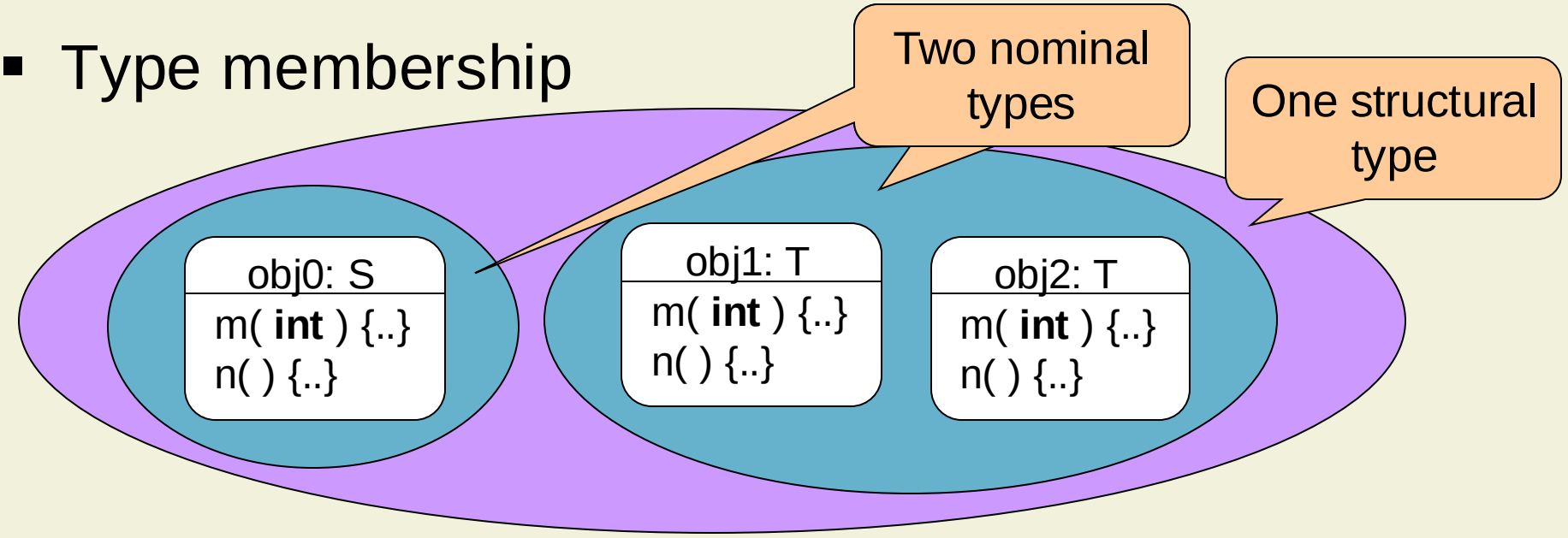
Types

- 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

Dynamic Type Checking

- Variables, methods, and expressions of a program are typically not annotated with types
- 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

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 features that would be hard to type-check statically, e.g., dynamic code generation

JavaScript

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

Bypassing Static Type Checks

- Some statically-typed languages 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

Gradual Typing

- Some dynamically-typed languages provide optional static type checking
  - mypy for Python
  - TypeScript for JavaScript
- Typically, an “Any” type indicates that an expression is not statically typed
  - No static type checks for “Any”
  - Type safety is guaranteed by run-time checks

Optional type annotation

```
def foo(s: str) -> str
```
Python

```
def bar1(x: Any) -> Any:
    return foo(x)
```

```
def bar2(x):
    return foo(x)
```

```
def bar3( ):
    return foo(1)
```

```
def bar4( ) -> int:
    return foo(‘Hello’)
```

Static vs. Dynamic Type Checking

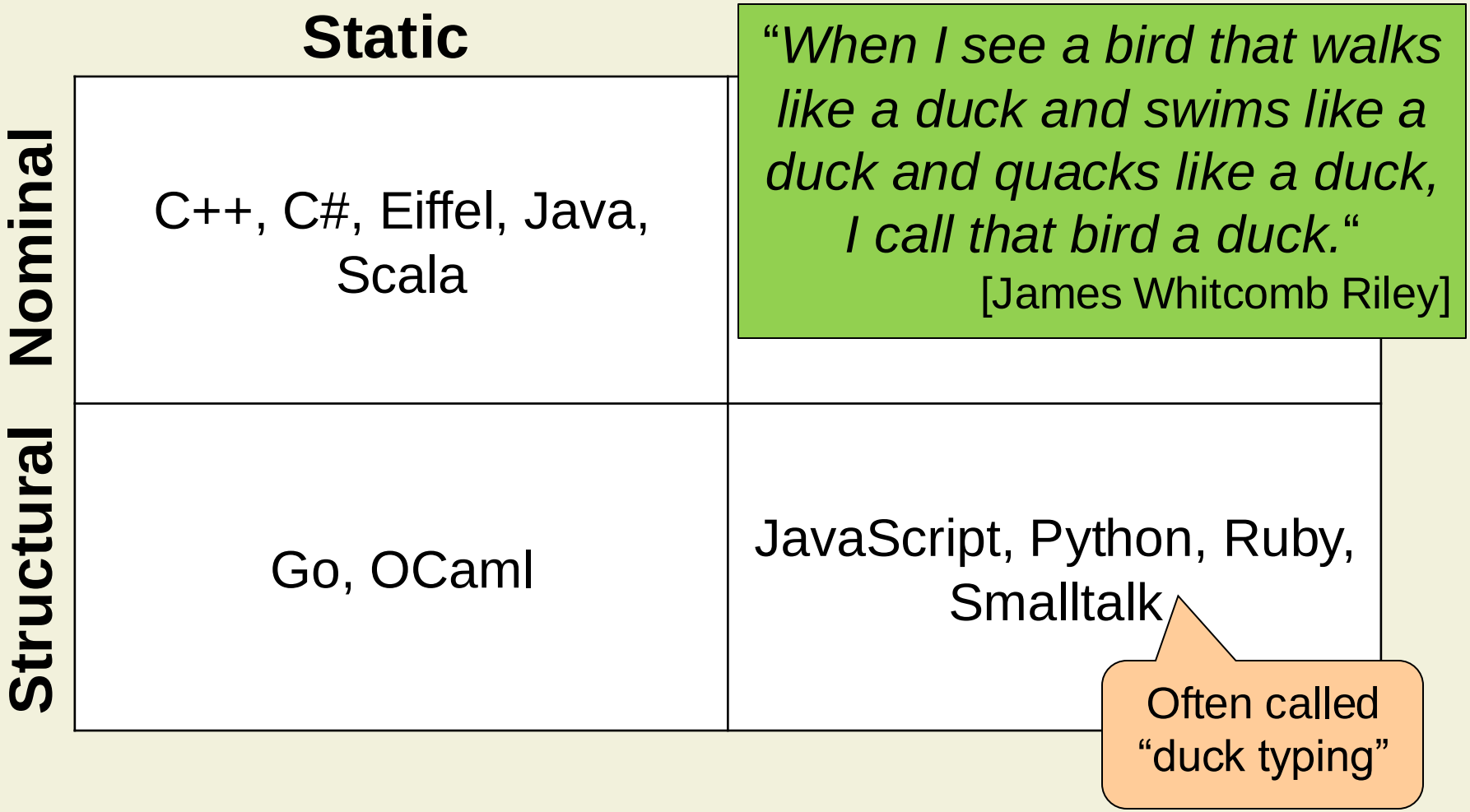
Advantages of static checking

- Static safety: More errors are found at compile time
- Readability: Types are excellent documentation
- Efficiency: Type information enables 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



2. Types and Subtyping

2.1 Types

2.2 Subtyping

2.3 Behavioral Subtyping

Classification in Software Technology

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

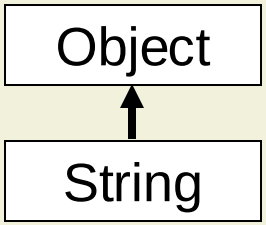
- Syntactic classification
  - Subtype objects can understand at least the messages that supertype objects can understand

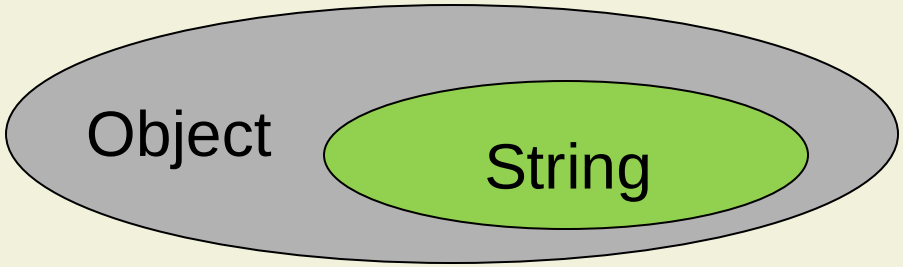
- Semantic classification
  - Subtype objects provide at least the behavior of supertype objects

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 ) {…}
  o( ) {…}
}
```

```
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

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[ ]
- 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

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
- 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()
}
```

(reminder: signature with nominal types)

- Static type checking
  - Additional supertypes can be introduced on demand

```
func printData(c interface {
    isEmpty() bool
    iterator() iter.Seq[ string ]
}) { … }
```

Go

- 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	Dynamic checks typically do not involve type directly, but rather the availability of operations
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 heap 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

Verification, code reviews

- Static safety: More errors are found at compile time
- Complexity: Automatic static contract checking is difficult
- Large overhead: Verification requires extensive contracts

Dynamic checking

Run-time assertion checking

- Expressiveness: Not all properties can be checked (efficiently) at run time
- Efficient bug-finding: Complements testing
- Low overhead: Partial contracts are useful

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

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

Checking Behavioral Subtyping

- Static checking, e.g., as part of code reviews
  - For each override S.m of T.m check for all parameters, heaps, and results

$$Pre_{T.m} \Rightarrow Pre_{S.m}$$
$$Post_{S.m} \Rightarrow Post_{T.m}$$

  - For each subtype S <: T check for all heaps

$$Inv_S \Rightarrow Inv_T$$
$$Cons_S \Rightarrow Cons_T$$

- Dynamic checking
  - No explicit checking of behavioral subtyping
  - Check the required properties at the beginning and end of each method execution

Improved Postcondition Rule

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

$$Post_{S.m} \Rightarrow Post_{T.m}$$

- Any caller that wants to use the supertype postcondition must establish the supertype precondition
- Improved rule (attempt):

$$Pre_{T.m} \Rightarrow (Post_{S.m} \Rightarrow Post_{T.m})$$

```
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)

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

$$Post_{S.m} \Rightarrow Post_{T.m}$$

- Any caller that wants to use the supertype postcondition must establish the supertype precondition
- Improved rule (definite):

$$old(Pre_{T.m}) \Rightarrow (Post_{S.m} \Rightarrow Post_{T.m})$$

```
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;
}
```

Automatic Checking of Behav. Subtyping

- Assume contracts are part of the program
- A static checker would have to check logical entailments, for example:

$$\text{old}(\text{Pre}_{T.m}) \Rightarrow (\text{Post}_{S.m} \Rightarrow \text{Post}_{T.m})$$

- But: entailment is undecidable

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

```
class Sub extends Super {

  // ensures result == 2
  int foo( int p ) { … }        }
```

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

Behavioral Nominal Subtyping

- Programmers should check behavioral subtyping when introducing subtype relations to ensure that polymorphic code works as expected
  - For instance, during code reviews
  - Checks can be performed on informal documentation or on formal contracts

- For languages with support for contracts
  - Checks cannot be fully automated due to undecidability
  - Specification inheritance is a technique to enforce behavioral subtyping by construction (not discussed here)

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)

- Type system should introduce a subtype relation only if behavioral subtyping rules are satisfied

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

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

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

- But these checks cannot be automated reliably, even if the program contains formal contracts

- Structural subtyping ignores the behavior!

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

References

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- Krishna Kishore Dhara and Gary T. Leavens: *Forcing Behavioral Subtyping through Specification Inheritance*. ICSE 1996