

Concepts of Object-Oriented Programming

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Programming Methodology Group

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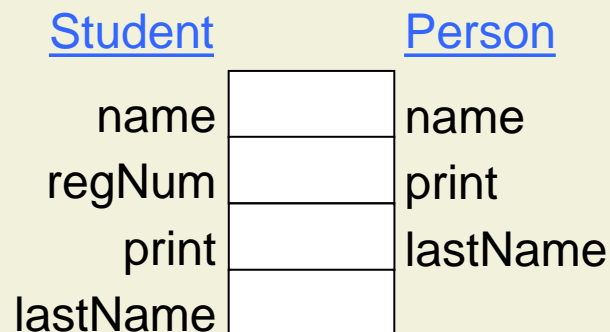
ETH zürich

C-Example Revisited

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

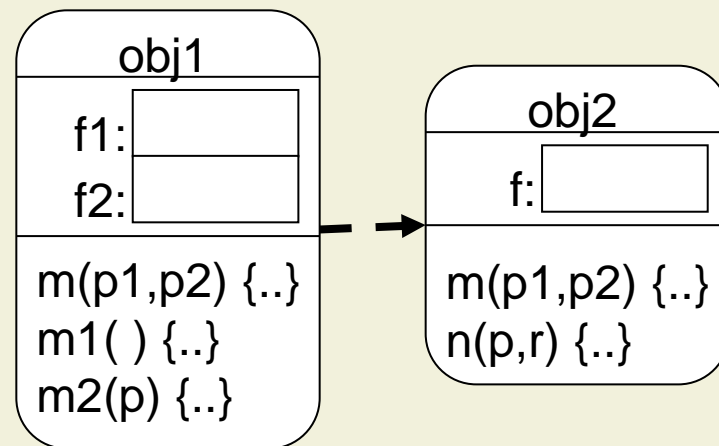
```
typedef struct sStudent Student;
struct sStudent {
    String name;
    int regNum;
    void  ( *print )( Student* );
    String ( *lastName )( Student* );
};
```

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



Message not Understood

- Objects access fields and methods of other objects



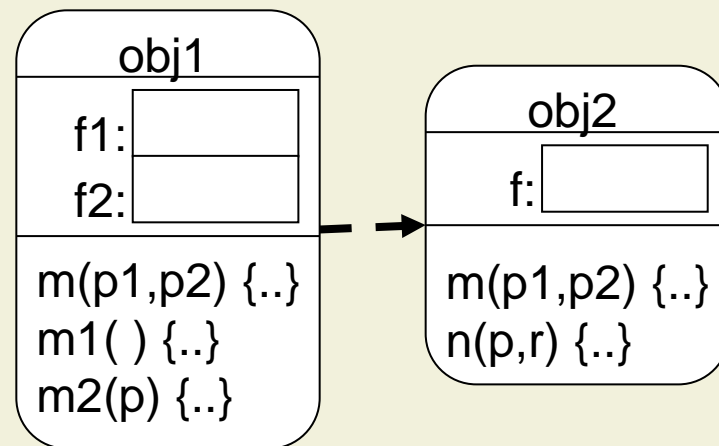
...

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

```
s = obj2.f;
```

Message not Understood

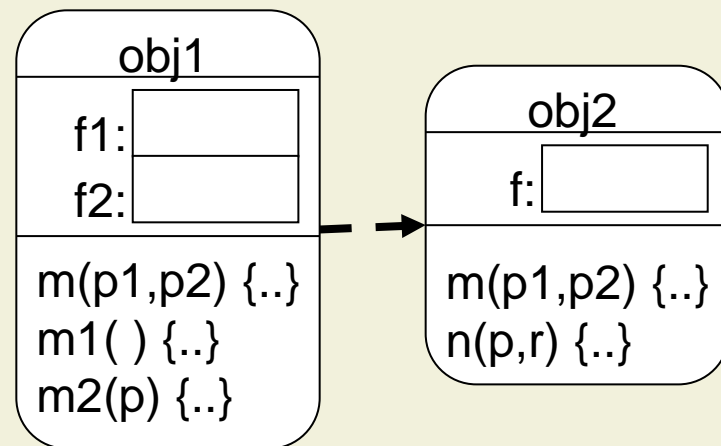
- Objects access fields and methods of other objects
- A safe language **detects situations** where the receiver object does not have the accessed field or method



```
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s = obj2.f;
```

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**

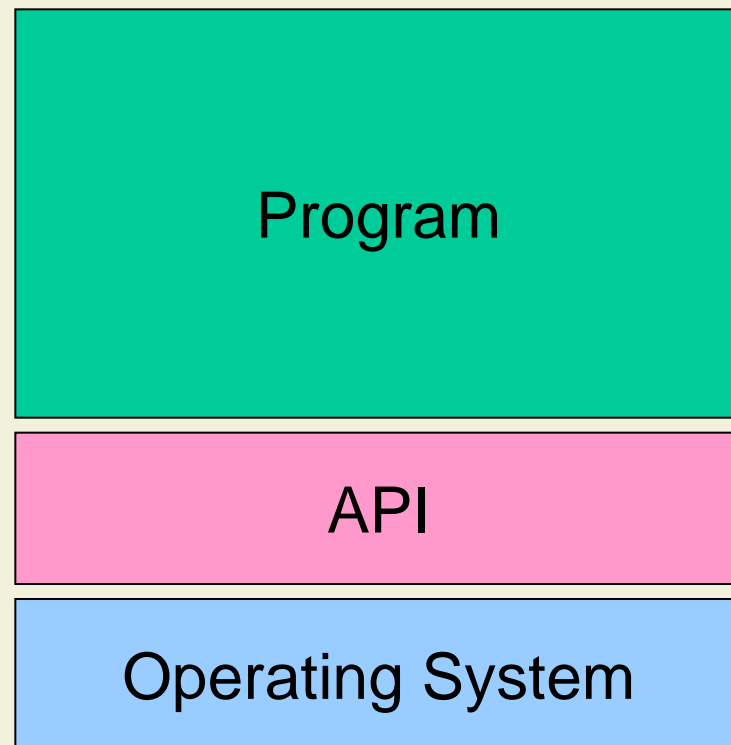


```
...  
r = obj2.m( 0, 1 );  
s = obj2.f;
```

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

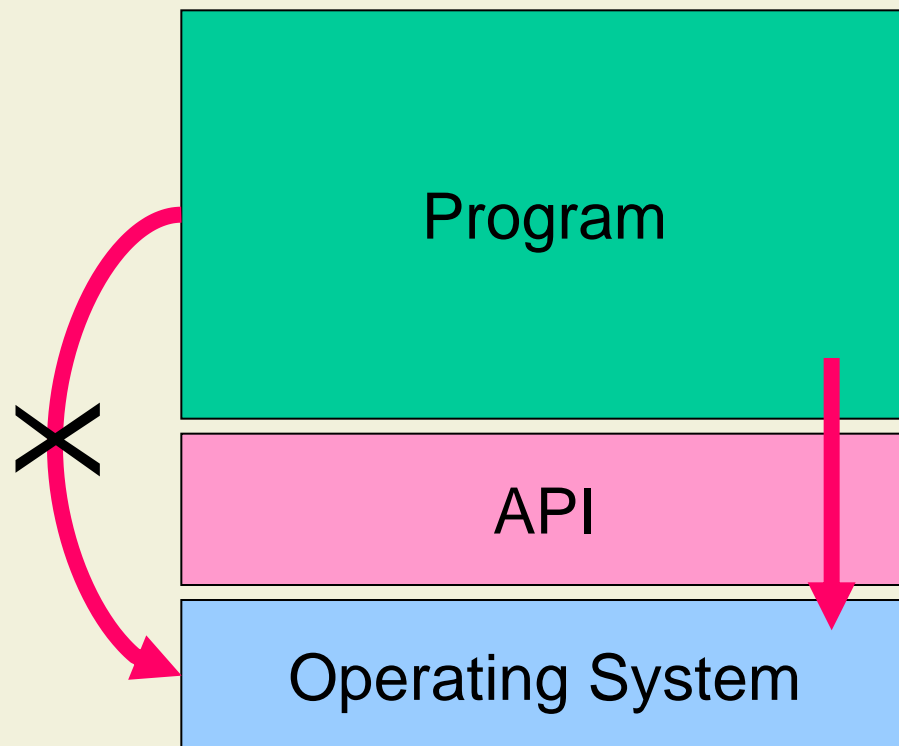
Java Security Model (Sandbox)

- 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**



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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 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

Weak vs. Strong Typing: Example

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int main( int argc, char** argv ) {  
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1628878672

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int main( int argc, char** argv ) {  
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}
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C

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

Java

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Java

Compile-time error:
inconvertible types
found : java.lang.String
required: int

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```

Java

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, OCaml, Python, Ruby, Smalltalk

Nominal and Structural Types

- Type membership

obj0: S
m(int) {..}
n() {..}

obj1: T
m(int) {..}
n() {..}

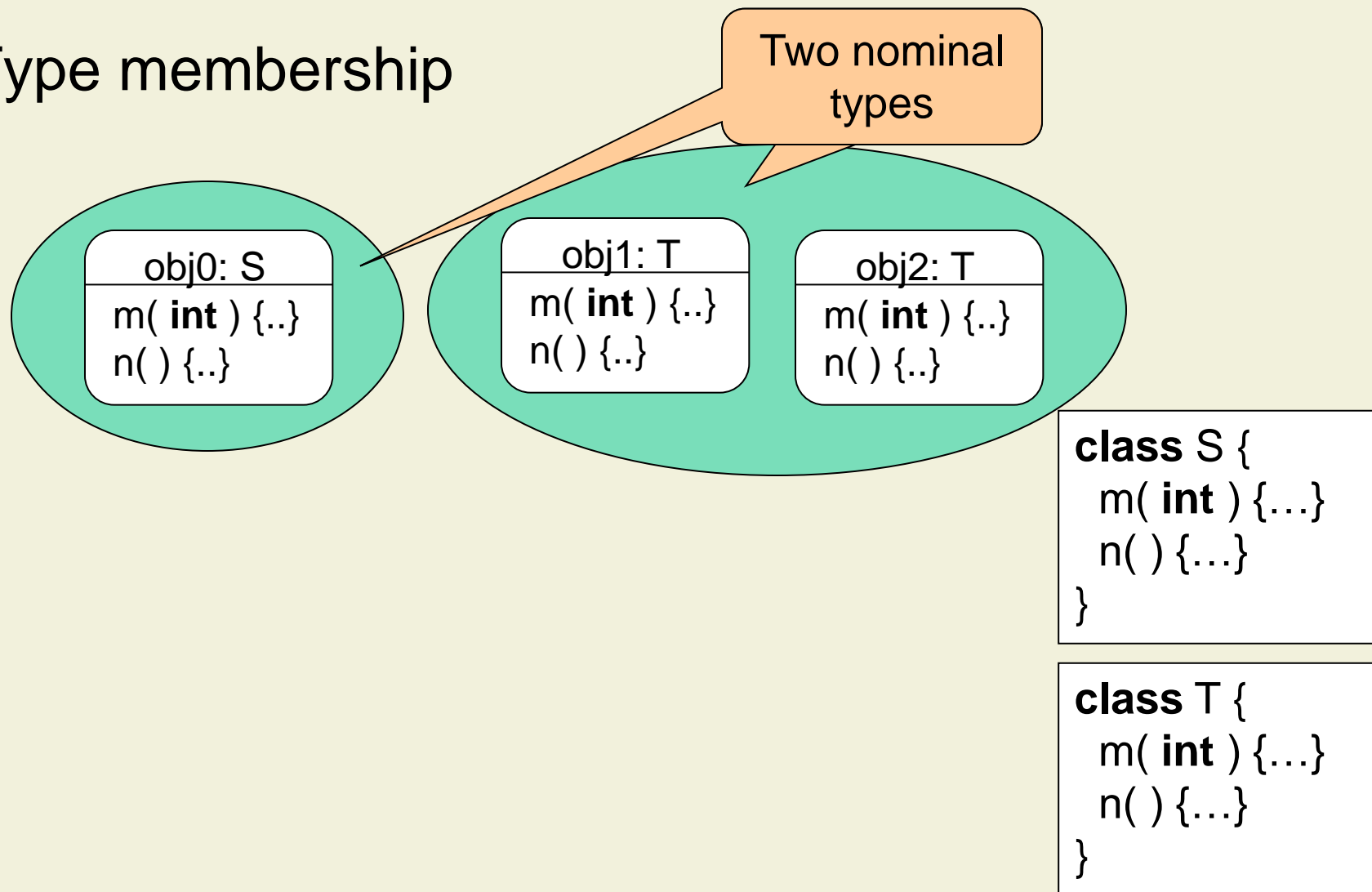
obj2: T
m(int) {..}
n() {..}

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

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

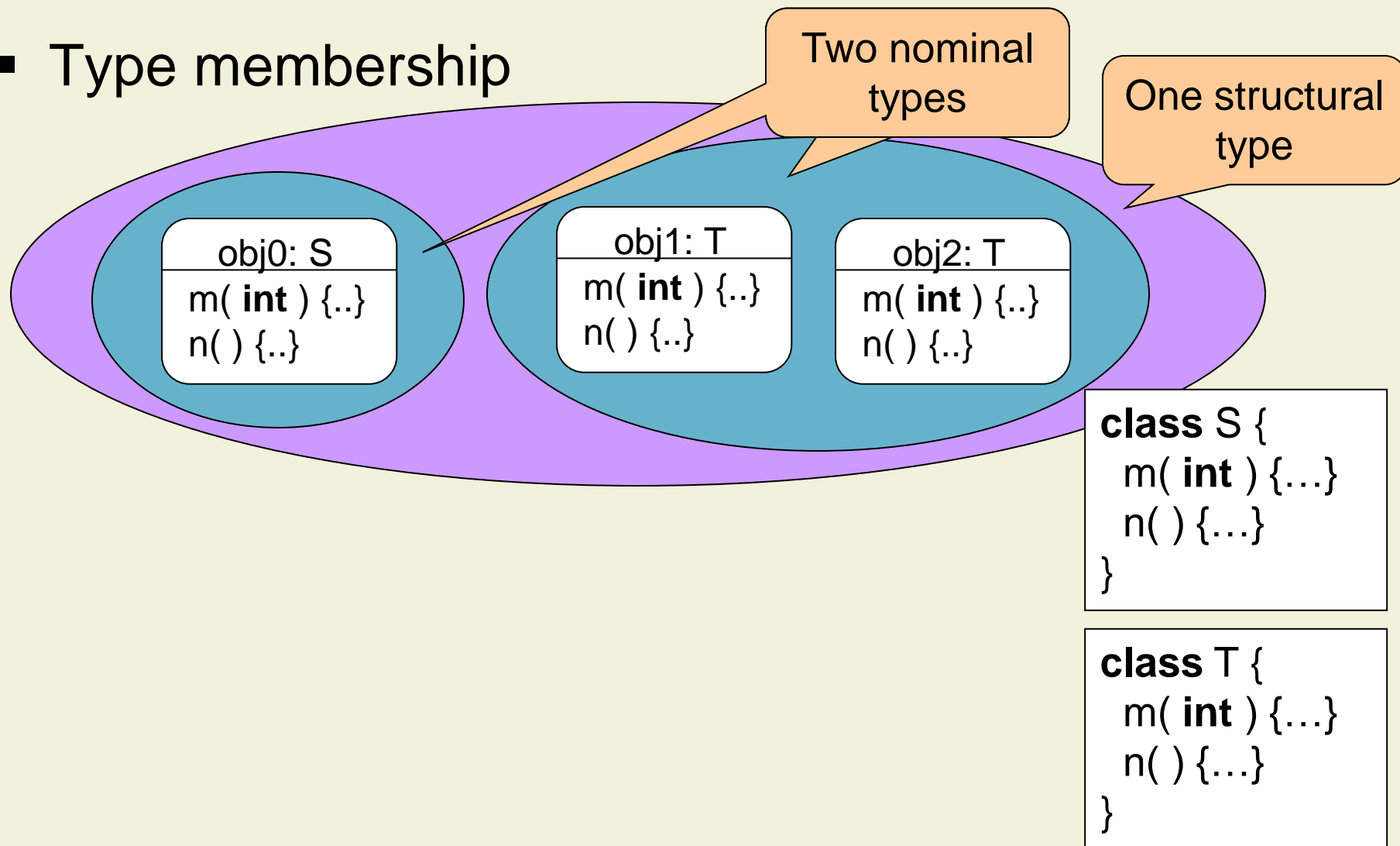
Nominal and Structural Types

- Type membership



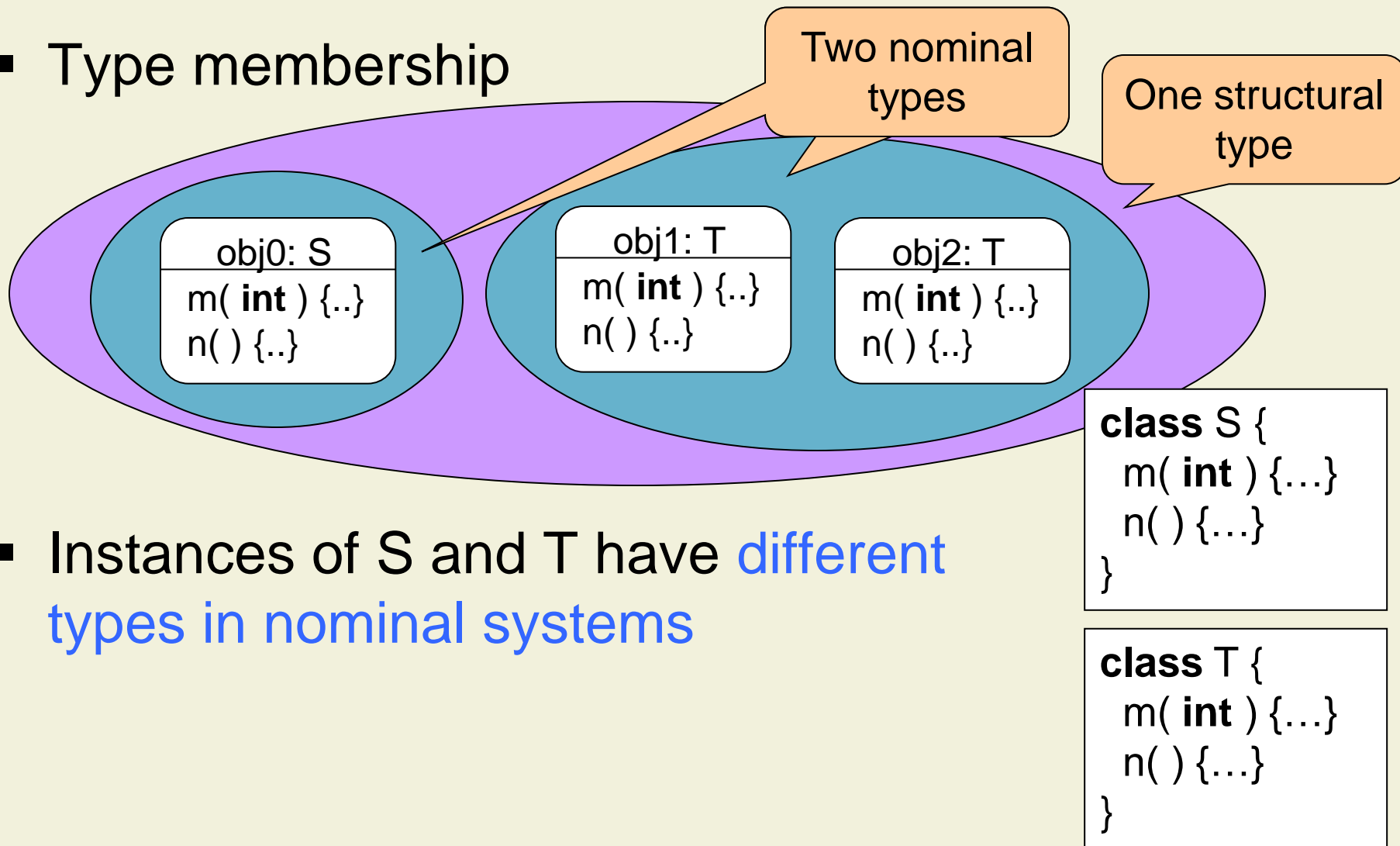
Nominal and Structural Types

■ Type membership



Nominal and Structural Types

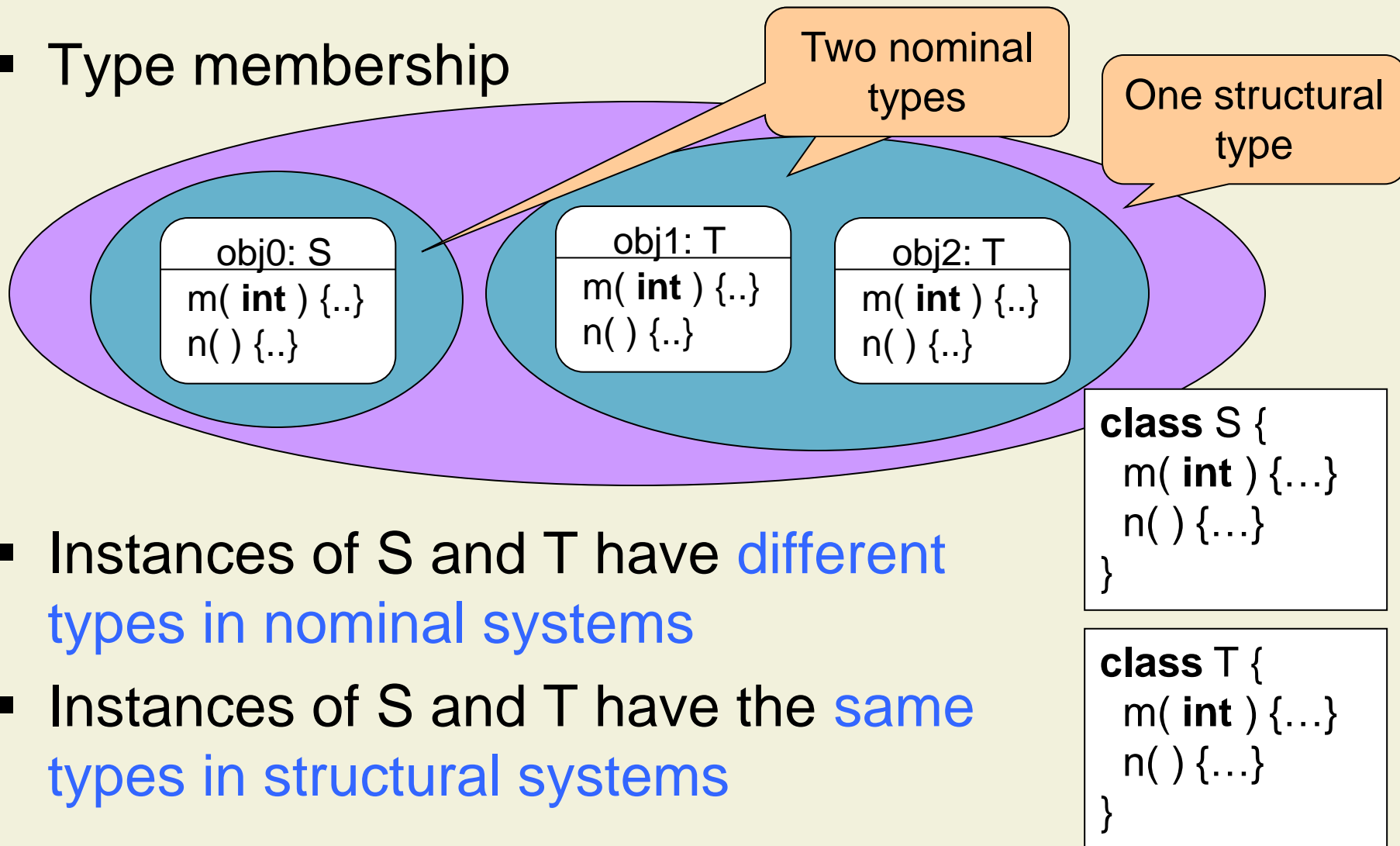
- Type membership



- Instances of S and T have **different types in nominal systems**

Nominal and Structural Types

- Type membership



- Instances of S and T have **different types in nominal systems**
- Instances of S and T have the **same types in structural systems**

Static Type Checking

- Each expression of a program has a type

“A string”

Java

5 + 7

Static Type Checking

- Each expression of a program has a type
- Types of variables and methods are declared explicitly or inferred

```
"A string"
```

```
Java
```

```
5 + 7
```

```
int a;
```

```
Java
```

```
boolean equals( Object o )
```

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

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```

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Java
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5 + 7
```

```
int a;
```

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Java
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```
boolean equals( Object o )
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```
a + 7
```

```
Java
```

```
"A number: " + 7
```

```
"A string".equals( null )
```

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

```
"A string"
```

```
Java
```

```
5 + 7
```

```
int a;
```

```
Java
```

```
boolean equals( Object o )
```

```
a + 7
```

```
Java
```

```
"A number: " + 7
```

```
"A string".equals( null )
```

```
a = "A string";
```

```
Java
```

```
"A string".equals( 1, 2 )
```

Compile-time
errors

Dynamic Type Checking

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

“A string”

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5 + 7

a = ...;

Python

def foo(o): ...

Dynamic Type Checking

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```
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```

```
Python
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```
5 + 7
```

```
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```

```
Python
```

```
def foo( o ): ...
```

```
a + 7
```

```
Python
```

```
"A number: " * 7
```

```
foo( None )
```

```
a = "A string"
```

```
Python
```

```
a = 7
```

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

```
"A string"
```

```
Python
```

```
5 + 7
```

```
a = ...;
```

```
Python
```

```
def foo( o ): ...
```

```
a + 7
```

```
Python
```

```
"A number: " * 7
```

```
foo( None )
```

```
a = "A string"
```

```
Python
```

```
a = 7
```

```
a = "A string" / 5
```

```
Python
```

```
foo( 5, 7 )
```

Run-time errors

Static Type Safety

- Definition:

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

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In every execution state, the value held by variable v is an element of the declared type of v

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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

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

```
oa[ 0 ] = s;
```

```
...
```

```
s = oa[ 0 ];
```

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

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;
```

```
...
```

```
s = (String) oa[ 0 ];
```

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

Expressiveness of Dynamic Type Systems

- Static checkers need to **approximate run-time behavior** (conservative checks)
- Dynamic checkers support features that would be hard to type-check statically, e.g., **dynamic code generation**

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

Python

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

JavaScript

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)
- Type safety is preserved via **run-time checks**

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

C#

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Existence of method
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C#

Result is
dynamic

Existence of method
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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**

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

Python

Optional type
annotation

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

Python

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

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Optional type annotation

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

Python

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

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

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Optional type annotation

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

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

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

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

Gradual Typing

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Optional type annotation

```
def foo(s: str) -> str
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def bar1(x: Any) -> Any:  
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```
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
- **Performance**: 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

	Static	Dynamic
Nominal	C++, C#, Eiffel, Java, Scala	Individual features of nominal, static languages
Structural	Go, OCaml	JavaScript, Python, Ruby, Smalltalk

Type Systems in OO-Languages

		Static	Dynamic
Structural	Nominal	C++, C#, Eiffel, Java, Scala	Individual features of nominal, static languages
	Nominal	Go, OCaml	JavaScript, Python, Ruby, Smalltalk <div>Often called “duck typing”</div>

Type Systems in OO-Languages

		Static
Structural	Nominal	<p>C++, C#, Eiffel, Java, Scala</p> <p><i>“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.”</i> [James Whitcomb Riley]</p>
	Structural	<p>Go, OCaml</p> <p>JavaScript, Python, Ruby, Smalltalk</p> <p>Often called “duck typing”</p>

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

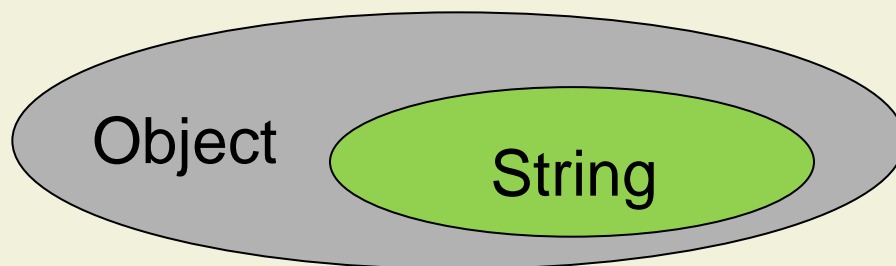
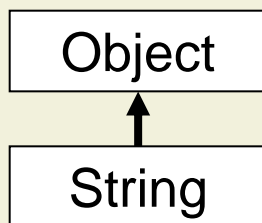
- Subtype objects provide at least the behavior of supertype objects

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**

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class S { m( int ) {...} }
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class S { m( int ) {...} }
```

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

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

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```
class T {
  m( int ) { ... }
  o( ) { ... }
}
```

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}
```

```
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( )  
}
```

- Sub narrows Super's interface

Existence

```
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  void foo( ) { ... }  
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}  
  
class Sub <: Super {  
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  // 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

Existence

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  void foo( ) { ... }  
  void bar( ) { ... }  
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}
```

```
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( ) { ... }  
}
```

Accessibility

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

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

- At run time, m could access a private method of Sub, thereby violating information hiding

Accessibility

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class Super {  
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    public void bar( ) { ... }  
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    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 ) { ... }  
}
```

Overriding: Parameter Types

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class Sub <: Super {  
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  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

Overriding: Parameter Types

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}
```

- 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( ) { ... }  
}
```

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

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;  
}
```

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

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 ] );  
}
```

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 $S[] <: T[]$

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 $S \leq T$ then $S[] \leq T[]$
- 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)

2. Types and Subtyping

2.1 Types

2.2 Subtyping

2.3 Behavioral 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  
    ...  
  
    void add( Object e ) { ... }  
}
```

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  
  
    ...  
    // 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; }  
  
    ...  
}
```

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; }  
  
    ...  
}
```

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

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  $0 \leq n \ \&\& \ n < 5$   
  void foo( int n ) {  
    char[ ] tmp = new char[ 5 ];  
    tmp[ n ] = 'X';  
  }  
}
```

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';  
  }  
}
```

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 );  
}
```

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( ) );
```

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  $0 < \text{result}$   
  int foo( ) {  
    return 1;  
  }  
}
```

Rules for Subtyping: Postconditions

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

```
class Sub extends Super {  
  // ensures  $0 \leq \text{result}$   
  int foo( ) {  
    return 0;  
  }  
}
```

Rules for Subtyping: Postconditions

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

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

```
class Sub extends Super {  
  // ensures  $0 \leq \text{result}$   
  int foo( ) {  
    return 0;  
  }  
}
```

Rules for Subtyping: Postconditions

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

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

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

```
class Sub extends Super {  
  // ensures  $0 \leq \text{result}$   
  int foo( ) {  
    return 0;  
  }  
}
```

Rules for Subtyping: Postconditions

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

```
class Sub extends Super {  
  // ensures  $0 \leq \text{result}$   
  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; }  
}
```

Rules for Subtyping: Invariants

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

```
class Sub extends Super {  
  // invariant  $0 \leq n$   
  Sub( ) {  
    n = 0;  
  }  
}
```

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  $0 \leq n$   
  Sub( ) {  
    n = 0;  
  }  
}
```

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  $0 \leq n$   
  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( ) { }  
}
```

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;  
  }  
}
```

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() );  
}
```

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( ) );
```

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

$$\begin{array}{l} \text{Pre}_{T.m} \Rightarrow \text{Pre}_{S.m} \\ \text{Post}_{S.m} \Rightarrow \text{Post}_{T.m} \end{array}$$

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

$$\begin{array}{l} \text{Inv}_S \Rightarrow \text{Inv}_T \\ \text{Cons}_S \Rightarrow \text{Cons}_T \end{array}$$

- 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

$$\text{Post}_{S.m} \Rightarrow \text{Post}_{T.m}$$

Improved Postcondition Rule

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

$$\text{Post}_{S.m} \Rightarrow \text{Post}_{T.m}$$

```
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 ) { ... }  
}
```

Improved Postcondition Rule

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

$$\text{Post}_{S.m} \Rightarrow \text{Post}_{T.m}$$

```
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

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

$$\text{Post}_{S.m} \Rightarrow \text{Post}_{T.m}$$

- Any caller that wants to use the supertype postcondition must establish the supertype precondition

- Improved rule (attempt):

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

```
class Super {  
    // requires 0 < p  
    // ensures 0 < result  
    int foo( int p ) { ... }  
}
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  int foo( ) { ... }  
}
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  int foo( )  
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  int foo( ) { ... }  
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class Sub extends Super {  
  // requires true  
  // ensures p < result  
  int foo( )  
  { ... }  
}
```

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

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class Super {  
  int p;  
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  // 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;  
}
```

Improved Postcondition Rule (c't)

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

$$\text{Post}_{S.m} \Rightarrow \text{Post}_{T.m}$$

- Any caller that wants to use the supertype postcondition must establish the supertype precondition

- Improved rule (definite):

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

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

```
class Sub extends Super {  
  // requires true  
  // ensures p < result  
  int foo( )  
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int client( Super s ) {  
  s.p = 5; int r = s.foo( );  
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Automatic Checking of Behav. Subtyping

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

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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 , $\text{result} ::$
 $\text{old}(p == p*p) \Rightarrow (\text{result} == 2 \Rightarrow p < \text{result})$

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**

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

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

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

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class Circle {  
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render( p ) {  
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class Cowboy {  
    draw( ) { ... }  
}
```

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

Behavioral Structural Subtyping (cont'd)

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

```
render( { void draw( )  
         requires P  
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  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() ); }
```

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

Behavioral Structural Subtyping (cont'd)

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```

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

- But these checks **cannot be automated** reliably, even if the program contains formal contracts
- **Structural subtyping ignores the behavior!**

Type Systems in OO-Languages

		Static	Dynamic
Structural	Nominal	<p>Sweetspot: Maximum static safety</p>	<p>Dynamic checks typically do not involve type directly, but rather the availability of operations</p>
	Structural	<p>Problems with semantics of subtypes (and type equivalence)</p>	<p>Sweetspot: Maximum flexibility</p>

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;  
  
    foo( q ) { ... }  
    ...  
}
```

Types as Contracts

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```
class Types {  
    Person p;  
    String foo( Person q ) { ... }  
    ...  
}
```

```
class Types {  
    p;  
    // invariant type( p ) <: Person  
  
    foo( q ) { ... }  
    ...  
}
```

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 ) { ... }  
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- Stronger invariant:
 - $\text{type}(p) <: S' \Rightarrow \text{type}(p) <: S$
requires $S' <: S$

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Covariance

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Covariance

■ Weaker precondition

- $\text{type}(q) <: T \Rightarrow \text{type}(q) <: T'$
requires $T <: T'$

Types as Contracts: Subtyping

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requires $S' <: S$

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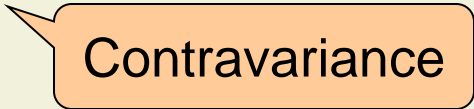
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Contravariance

Types as Contracts: Subtyping

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```

- Stronger invariant:
 - $\text{type}(p) <: S' \Rightarrow \text{type}(p) <: S$
requires $S' <: S$ 
- Weaker precondition
 - $\text{type}(q) <: T \Rightarrow \text{type}(q) <: T'$
requires $T <: T'$ 
- Stronger postcondition:
 - $\text{type}(\text{result}) <: U' \Rightarrow \text{type}(\text{result}) <: U$
requires $U' <: U$

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■ Weaker precondition

- $\text{type}(q) <: T \Rightarrow \text{type}(q) <: T'$
requires $T <: T'$

Contravariance

■ Stronger postcondition:

- $\text{type}(\text{result}) <: U' \Rightarrow$
 $\text{type}(\text{result}) <: U$
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`

Invariants over Inherited Fields

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

- 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