

Concepts of Object-Oriented Programming

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4. Types

4.1 Bytecode Verification

4.2 Parametric Polymorphism

Mobile Code: Motivation

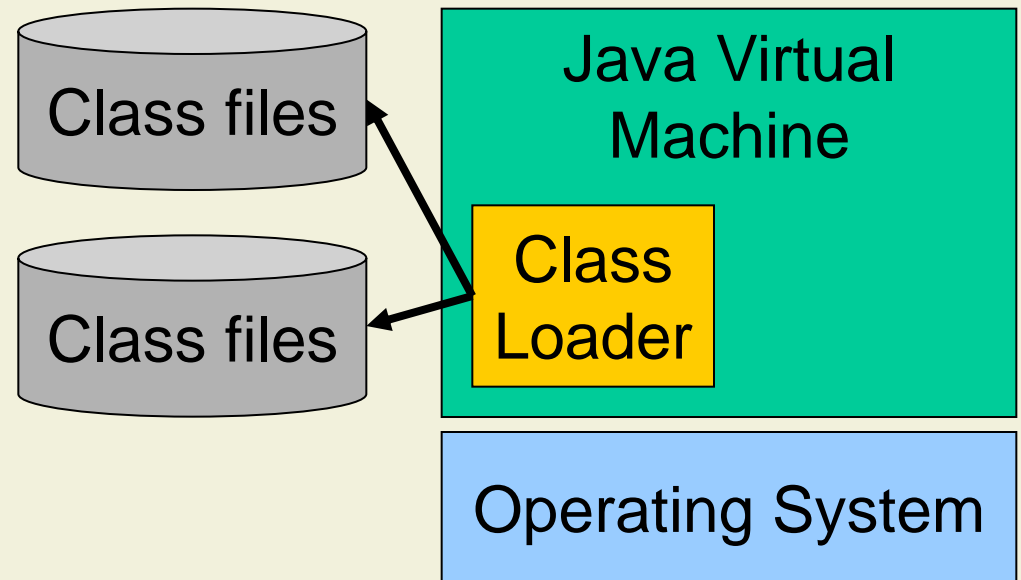
- Download and execution of code, e.g., Java applets
 - Web pages
 - Mobile devices

- Upload of code
 - Customizing servers

- Automatic distribution of code and patches in distributed systems

Class Loaders

- Programs are compiled to bytecode
 - Platform-independent format
 - Organized into class files
- Bytecode is interpreted on a virtual machine
- Class loader gets code for classes and interfaces on demand
- Programs can contain their own class loaders



Example: Specialized Class Loader

Error
handling
partly
omitted

```
public class MyLoader extends ClassLoader {  
    byte[ ] getClassData( String name ) { ... }  
  
    public synchronized Class loadClass( String name )  
        throws ClassNotFoundException {  
  
        Class c = findLoadedClass( name );  
        if ( c != null ) return c;  
  
        try { c = findSystemClass( name ); return c; }  
        catch ( ClassNotFoundException e ) { }  
  
        byte[ ] data = getClassData( name );  
        return defineClass( name, data, 0, data.length ); }  
}
```

Java

Security in Mobile Environments

- Mobile code cannot be trusted
 - Code may not be type safe
 - Code may destroy or modify data
 - Code may expose personal information
 - Code may crash the underlying VM
 - Code may purposefully degrade performance (denial of service)

- How to guarantee a minimum level of security?
 - Untrusted code producer
 - Untrusted compiler

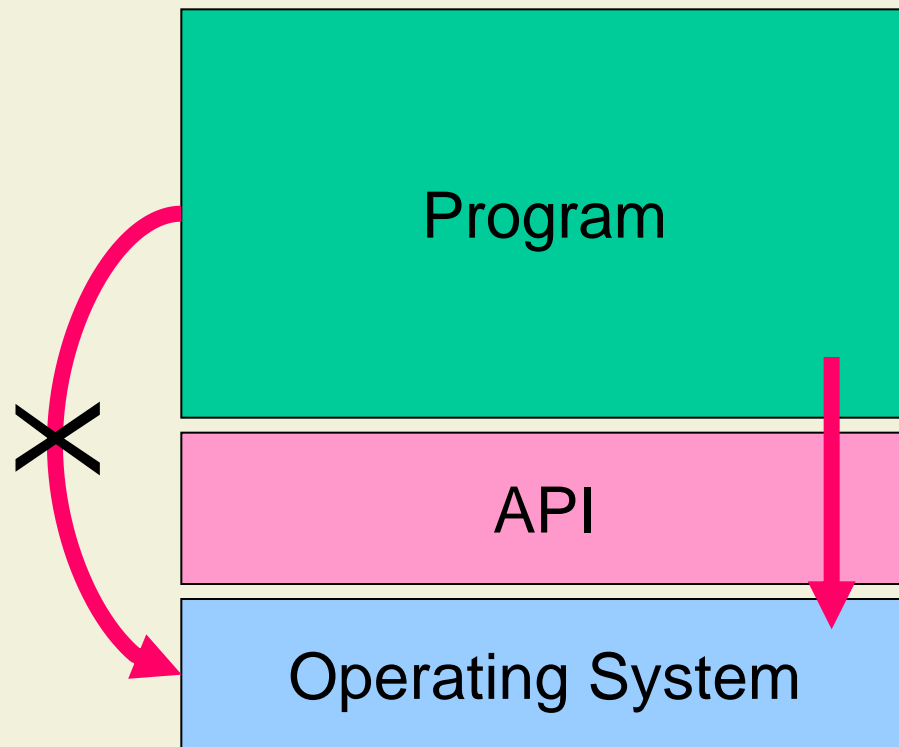
Security for Java Programs

■ Sandbox

- Applets get access to system resources only through an API
- Access control can be implemented

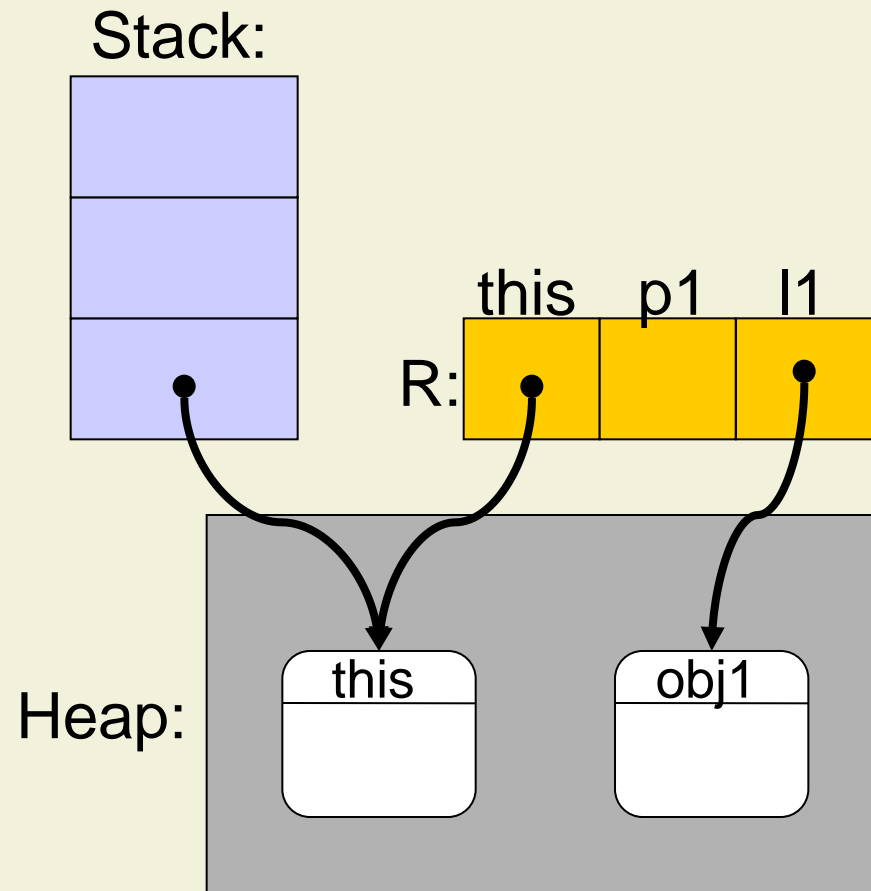
■ Security relies on

- Type safety
- Code does not by-pass sandbox



Java Virtual Machine

- JVM is stack-based
- Most operations pop operands from a stack and push a result
- Registers store method parameters and local variables
- Stack and registers are part of the method activation record

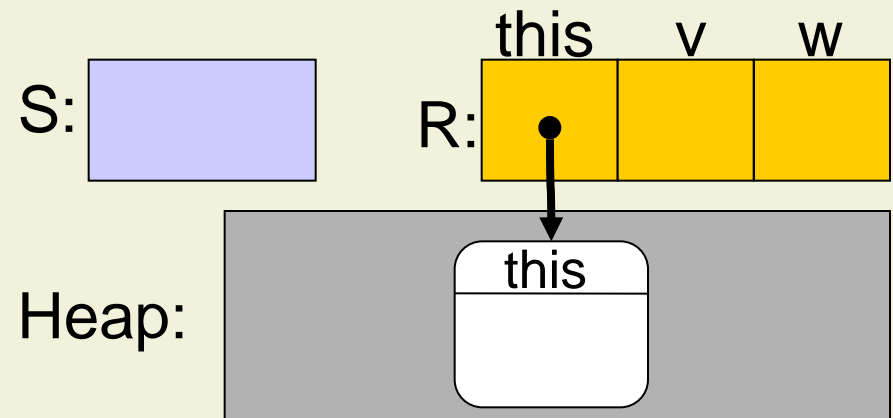


Java Bytecode

- Instructions are typed
- Load and store instructions access registers
- Control is handled by intra-method jumps (goto, conditional branches)

```
class C {  
  void m( ) {  
    int v;  
    Object w;  
    v = 5;  
    w = this;  
  }  
}
```

```
iconst 5  
istore 1  
aload 0  
astore 2  
return
```

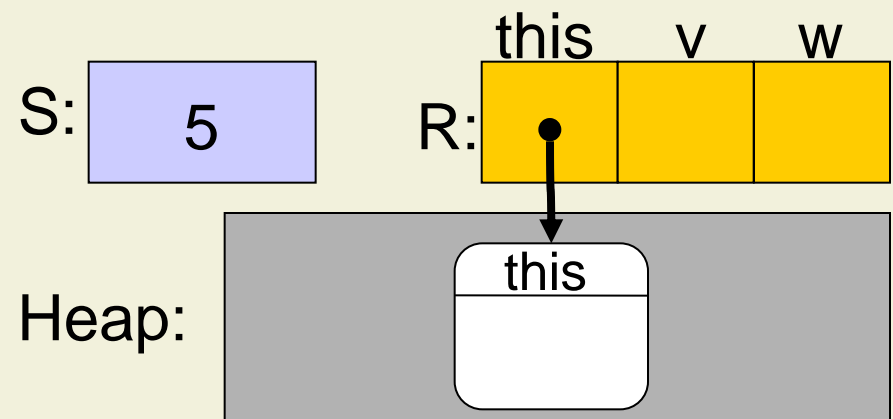


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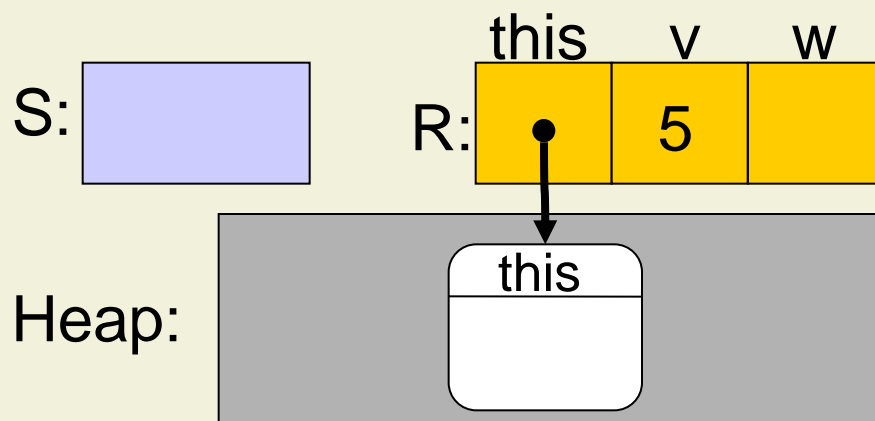


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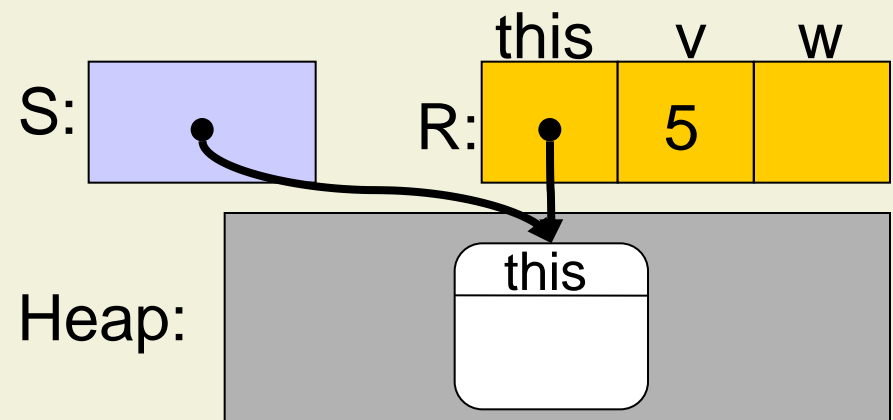


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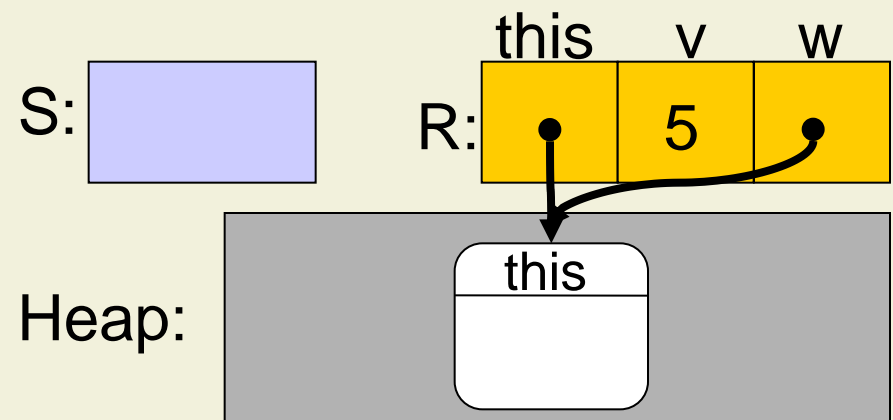


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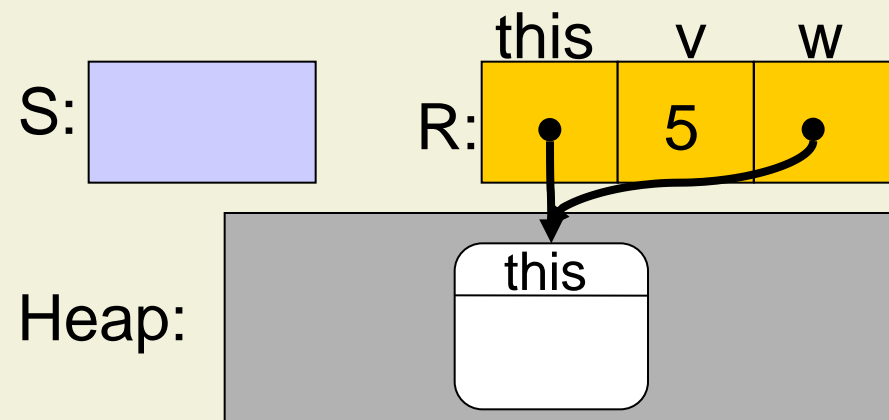


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```



Bytecode Verification

- Proper execution requires that
 - Each instruction is type correct
 - Only initialized variables are read
 - No stack over- or underflow occurs
 - Etc.

- Java Virtual Machine guarantees these properties
 - By **bytecode verification** when a class is loaded
 - By **dynamic checks at run time**

Bytecode Verification via Type Inference

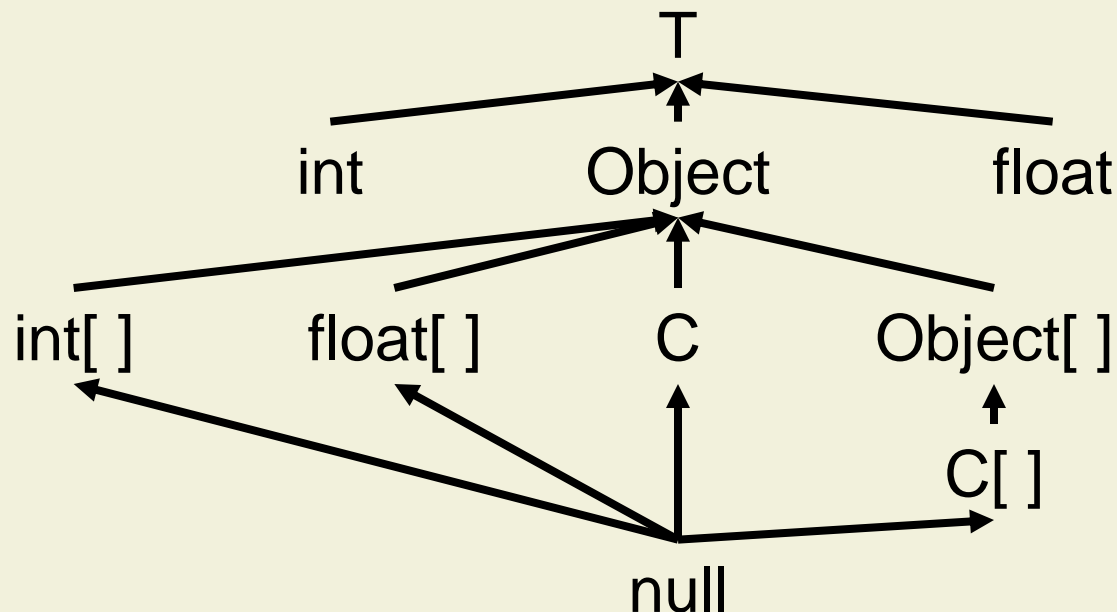
- The Bytecode verifier **simulates** the execution of the program
- Operations are performed on **types instead of values**
- For each instruction, a rule describes how the **operand stack and local variables** are modified

$$\begin{aligned} i: (S, R) &\rightarrow (S', R') \\ \text{iadd}: (\text{int.int.S}, R) &\rightarrow (\text{int.S}, R) \end{aligned}$$

- Errors are denoted by the **absence of a transition**
 - Type mismatch
 - Stack over- or underflow

Types of the Inference Engine

- Primitive types
- Object and array reference types
- null type for the null reference
- T (“top”) for uninitialized registers



Selected Rules

- Maximum stack size (MS) and maximum number of parameters and local variables (MR) are stored in the classfile
- Rule for method invocation uses method signature (no jump)

iconst n:

$(S, R) \rightarrow (\text{int}.S, R)$, if $|S| < MS$

iload n:

$(S, R) \rightarrow (\text{int}.S, R)$,
if $0 \leq n < MR \wedge R(n) = \text{int} \wedge |S| < MS$

astore n:

$(t.S, R) \rightarrow (S, R\{n \leftarrow t\})$,
if $0 \leq n < MR \wedge t <: \text{Object}$

invokevirtual C.m. σ :

$(t'_n \dots t'_1.t'.S, R) \rightarrow (r.S, R)$, if
 $\sigma = r(t_1, \dots, t_n) \wedge t' <: C \wedge t'_i <: t_i$

Example

this

v

w

```
int v;
Object w;
v = 5;
w = this;
```

```
iconst 5
istore 1
aload 0
astore 2
return
```

```
( [ ] , [ C,T,T ] ) →
( int , [ C,T,T ] ) →
( [ ] , [ C,int,T ] ) →
( C , [ C,int,T ] ) →
( [ ] , [ C,int,C ] )
```

```
int v;
Object w;
v = 5;
w = v;
```

```
iconst 5
istore 1
iload 1
astore 2
return
```

```
( [ ] , [ C,T,T ] ) →
( int , [ C,T,T ] ) →
( [ ] , [ C,int,T ] ) →
( int , [ C,int,T ] )
stuck
```

astore
expects an
object type
on top of
the stack!

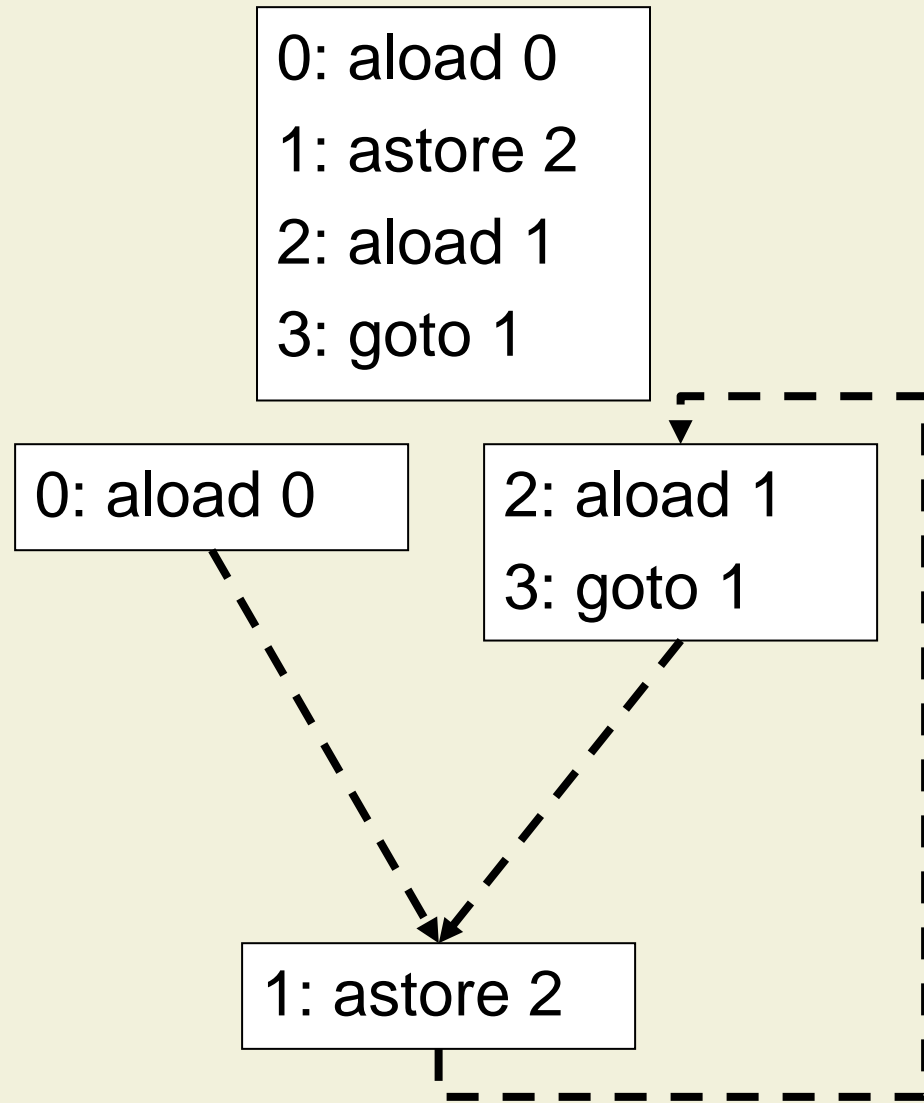
Smallest Common Supertype

- Jumps may lead to
joins in control flow

```
0: aload 0  
1: astore 2  
2: aload 1  
3: goto 1
```

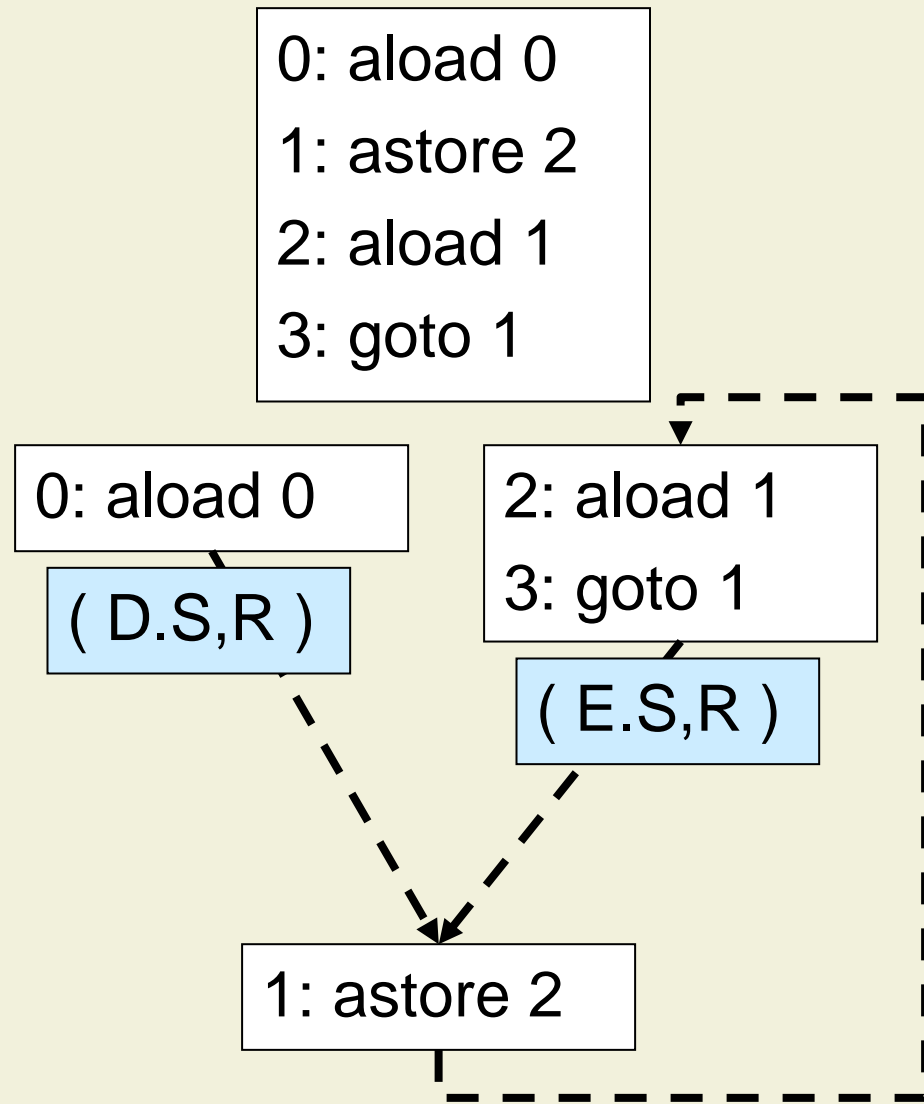
Smallest Common Supertype

- Jumps may lead to **joins in control flow**
- Instructions can have **several predecessors**



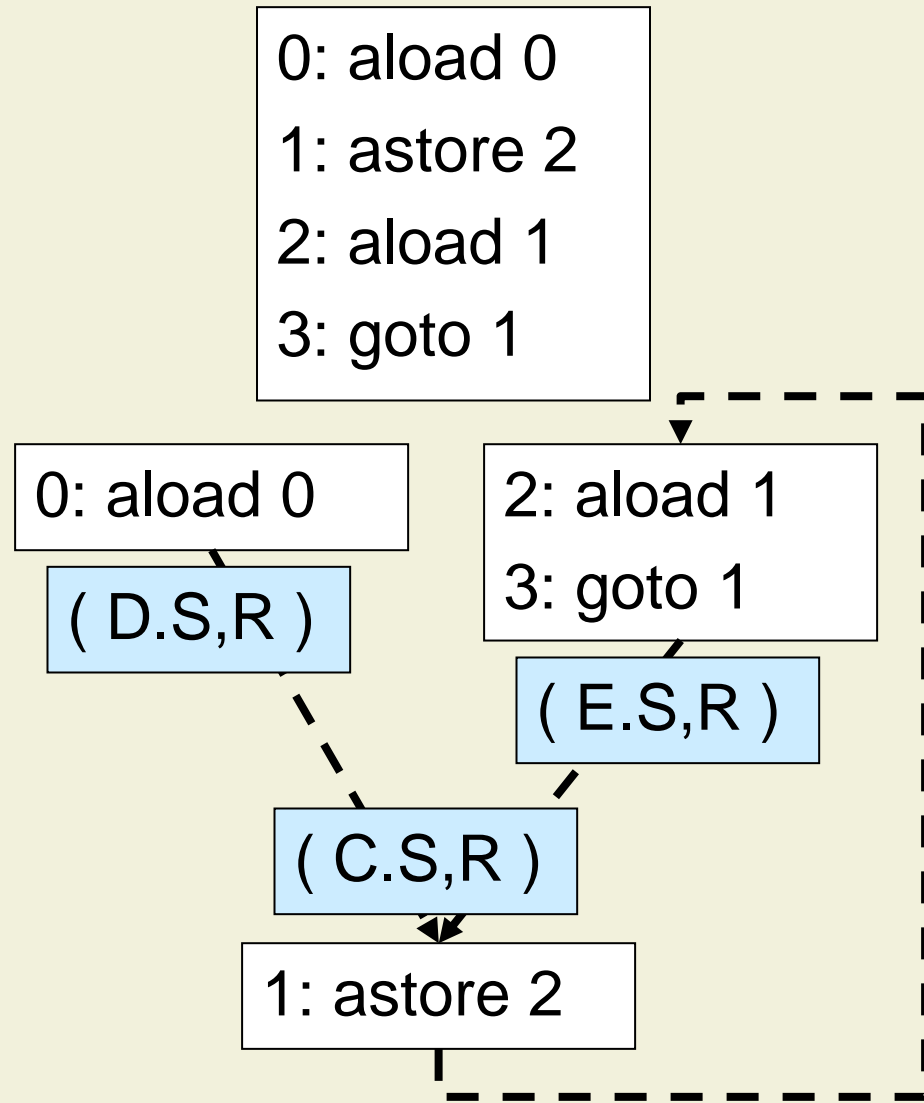
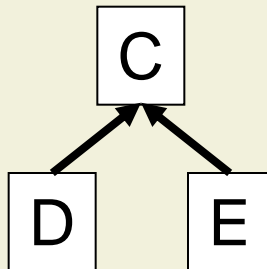
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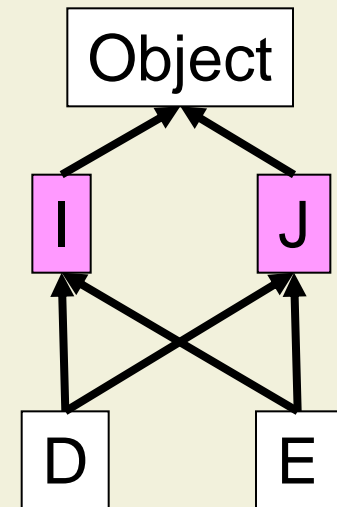
Smallest Common Supertype

- Jumps may lead to **joins in control flow**
- Instructions can have **several predecessors**
- **Smallest common supertype** is selected (T if no other common supertype exists)



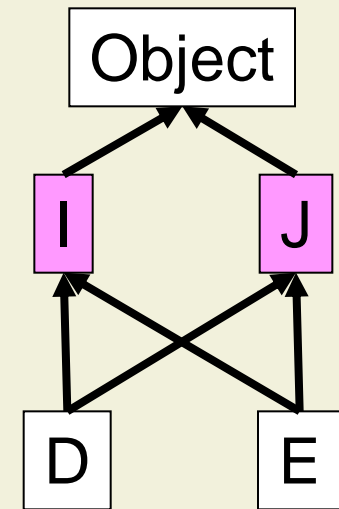
Handling Multiple Subtyping

- With multiple subtyping, the **smallest common supertype** may not be well-defined
- JVM solution
 - Ignore interfaces
 - Treat all interface types as Object
 - Works because of single inheritance of classes



Handling Multiple Subtyping

- With multiple subtyping, the **smallest common supertype** may not be well-defined
- JVM solution
 - Ignore interfaces
 - Treat all interface types as Object
 - Works because of single inheritance of classes
- Problem
 - **invokeinterface** I.m cannot check whether target object implements I
 - Run-time check is necessary



Inference Algorithm

- Inference is a fixpoint iteration

```
in( 0 ) := ( [ ] , [ P0, ..., Pn, T, ..., T ] )  
worklist := { i | instri is an instruction of the method }  
while worklist ≠ ∅ do  
  i := min( worklist )  
  remove i from worklist  
  out( i ) := apply_rule( instri, in( i ) )  
  foreach q in successors( i ) do  
    in( q ) := pointwise_scs( in( q ), out( i ) )  
    if in( q ) has changed then worklist := worklist ∪ { q }  
  end  
end
```

Pointwise SCS

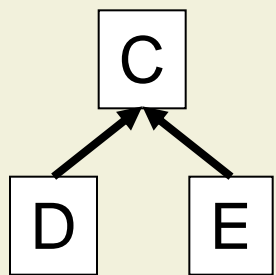
- $\text{scs}(s, t)$ is the smallest common supertype of s and t

$$\begin{aligned} \text{pointwise_scs} \big(& ([s_1, \dots, s_k], [t_0, \dots, t_n]), \\ & ([s'_1, \dots, s'_k], [t'_0, \dots, t'_n]) \big) = \\ & ([\text{scs}(s_1, s'_1), \dots, \text{scs}(s_k, s'_k)], [\text{scs}(t_0, t'_0), \dots, \text{scs}(t_n, t'_n)]) \end{aligned}$$

- pointwise_scs is undefined for stacks of different heights
 - Bytecode verification results in an error

Inference Example

0: aload 0
1: astore 2
2: aload 1
3: goto 1



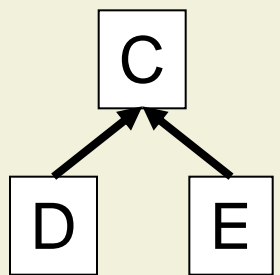
worklist

- 0 1 2 3

	in	out
0:	([], [D,E,T])	
1:		
2:		
3:		

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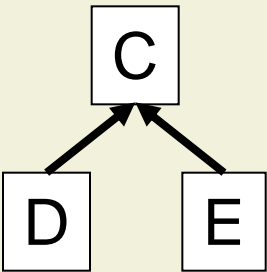
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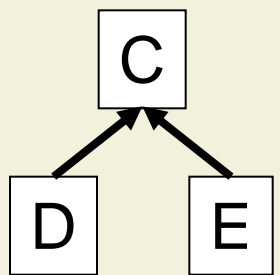
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	in	out
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1:		
2:		
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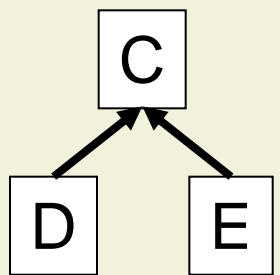
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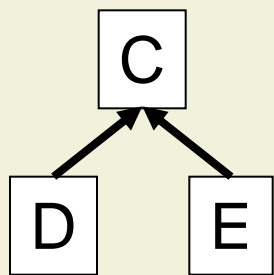
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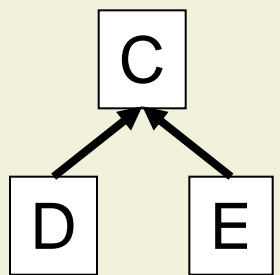
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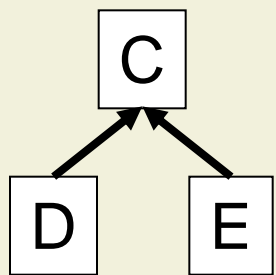
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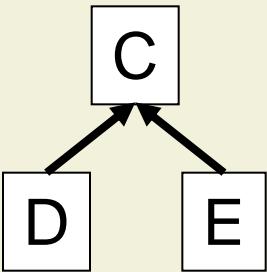
worklist

3

	in	out
0:	$([], [D, E, T])$	$([D], [D, E, T])$
1:	$([D], [D, E, T])$	$([], [D, E, D])$
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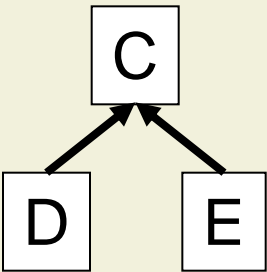
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1:	$([D], [D, E, T])$	$([], [D, E, D])$
2:	$([], [D, E, D])$	$([E], [D, E, D])$
3:		

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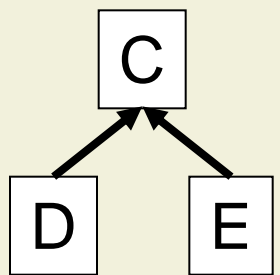
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0:	$([], [D, E, T])$	$([D], [D, E, T])$
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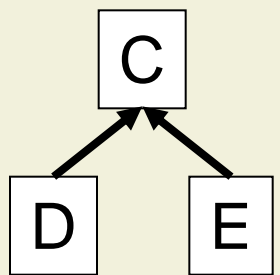
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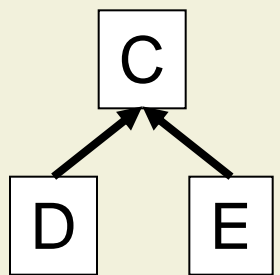
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2:	$([], [D, E, D])$	$([E], [D, E, D])$
3:	$([E], [D, E, D])$	$([E], [D, E, D])$

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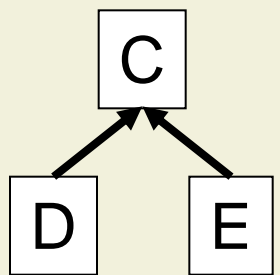
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1:	$([D], [D, E, T])$ $([C], [D, E, T])$	$([], [D, E, D])$
2:	$([], [D, E, D])$	$([E], [D, E, D])$
3:	$([E], [D, E, D])$	$([E], [D, E, D])$

Inference Example

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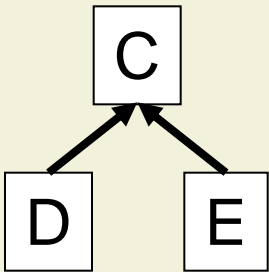
worklist

1

	in	out
0:	([], [D,E,T])	([D], [D,E,T])
1:	([D], [D,E,T]) ([C], [D,E,T])	([], [D,E,D])
2:	([], [D,E,D])	([E], [D,E,D])
3:	([E], [D,E,D])	([E], [D,E,D])

Inference Example

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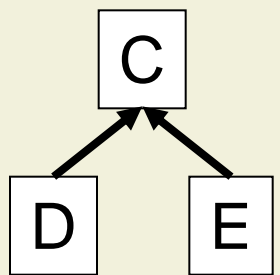
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	in	out
0:	([], [D,E,T])	([D], [D,E,T])
1:	([D], [D,E,T]) ([C], [D,E,T])	([], [D,E,D])
2:	([], [D,E,D])	([E], [D,E,D])
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Inference Example

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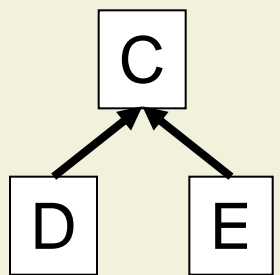
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	in	out
0:	([], [D,E,T])	([D], [D,E,T])
1:	([D], [D,E,T]) ([C], [D,E,T])	([], [D,E,D]) ([], [D,E,C])
2:	([], [D,E,D])	([E], [D,E,D])
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Inference Example

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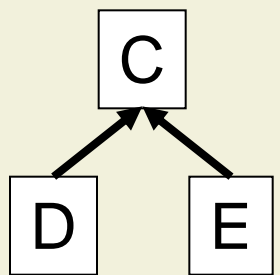
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	in	out
0:	([] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([] , [D,E,D]) ([] , [D,E,C])
2:	([] , [D,E,D]) ([] , [D,E,C])	([E] , [D,E,D])
3:	([E] , [D,E,D])	([E] , [D,E,D])

Inference Example

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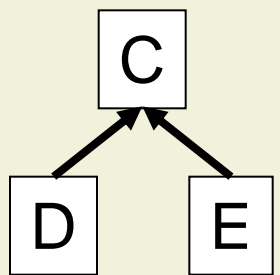
worklist

2

	in	out
0:	$([], [D, E, T])$	$([D], [D, E, T])$
1:	$([D], [D, E, T])$ $([C], [D, E, T])$	$([], [D, E, D])$ $([], [D, E, C])$
2:	$([], [D, E, D])$ $([], [D, E, C])$	$([E], [D, E, D])$
3:	$([E], [D, E, D])$	$([E], [D, E, D])$

Inference Example

0: aload 0
1: astore 2
2: aload 1
3: goto 1



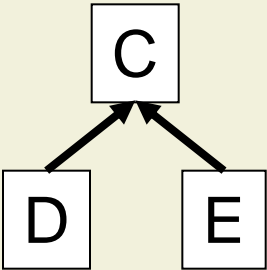
worklist



	in	out
0:	([] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([] , [D,E,D]) ([] , [D,E,C])
2:	([] , [D,E,D]) ([] , [D,E,C])	([E] , [D,E,D])
3:	([E] , [D,E,D])	([E] , [D,E,D])

Inference Example

0: aload 0
1: astore 2
2: aload 1
3: goto 1



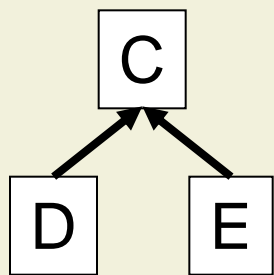
worklist



	in	out
0:	$([], [D, E, T])$	$([D], [D, E, T])$
1:	$([D], [D, E, T])$ $([C], [D, E, T])$	$([], [D, E, D])$ $([], [D, E, C])$
2:	$([], [D, E, D])$ $([], [D, E, C])$	$([E], [D, E, D])$ $([E], [D, E, C])$
3:	$([E], [D, E, D])$	$([E], [D, E, D])$

Inference Example

0: aload 0
1: astore 2
2: aload 1
3: goto 1



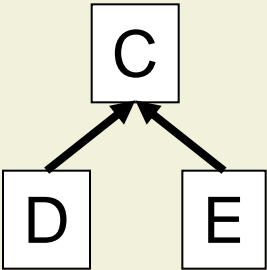
worklist



	in	out
0:	([], [D,E,T])	([D], [D,E,T])
1:	([D], [D,E,T]) ([C], [D,E,T])	([], [D,E,D]) ([], [D,E,C])
2:	([], [D,E,D]) ([], [D,E,C])	([E], [D,E,D]) ([E], [D,E,C])
3:	([E], [D,E,D]) ([E], [D,E,C])	([E], [D,E,D])

Inference Example

0: aload 0
1: astore 2
2: aload 1
3: goto 1



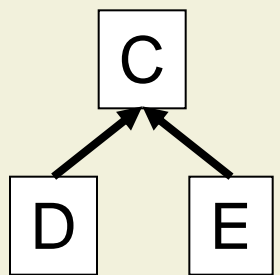
worklist

3

	in	out
0:	([], [D,E,T])	([D], [D,E,T])
1:	([D], [D,E,T]) ([C], [D,E,T])	([], [D,E,D]) ([], [D,E,C])
2:	([], [D,E,D]) ([], [D,E,C])	([E], [D,E,D]) ([E], [D,E,C])
3:	([E], [D,E,D]) ([E], [D,E,C])	([E], [D,E,D])

Inference Example

0: aload 0
1: astore 2
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3: goto 1



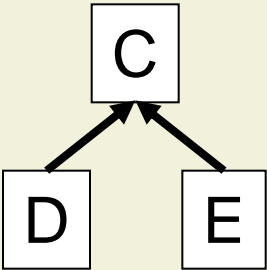
worklist



	in	out
0:	([], [D,E,T])	([D], [D,E,T])
1:	([D], [D,E,T]) ([C], [D,E,T])	([], [D,E,D]) ([], [D,E,C])
2:	([], [D,E,D]) ([], [D,E,C])	([E], [D,E,D]) ([E], [D,E,C])
3:	([E], [D,E,D]) ([E], [D,E,C])	([E], [D,E,D])

Inference Example

0: aload 0
1: astore 2
2: aload 1
3: goto 1



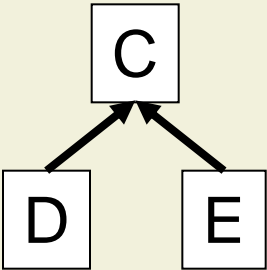
worklist



	in	out
0:	([], [D,E,T])	([D], [D,E,T])
1:	([D], [D,E,T]) ([C], [D,E,T])	([], [D,E,D]) ([], [D,E,C])
2:	([], [D,E,D]) ([], [D,E,C])	([E], [D,E,D]) ([E], [D,E,C])
3:	([E], [D,E,D]) ([E], [D,E,C])	([E], [D,E,D]) ([E], [D,E,C])

Inference Example

0: aload 0
1: astore 2
2: aload 1
3: goto 1



worklist



	in	out
0:	([] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([] , [D,E,D]) ([] , [D,E,C])
2:	([] , [D,E,D]) ([] , [D,E,C])	([E] , [D,E,D]) ([E] , [D,E,C])
3:	([E] , [D,E,D]) ([E] , [D,E,C])	([E] , [D,E,D]) ([E] , [D,E,C])

Type Inference: Discussion

■ Advantages

- Determines the **most general solution** that satisfies the type rules
- Might be more general than what is permitted by compiler
- Very little type information required in class file

■ Disadvantages

- Fixpoint computations may be slow
- Solution for interfaces is **imprecise** and **requires run-time checks**

■ Alternative: type checking (since Java 6)

Bytecode Verification via Type Checking

- Extend class file to store type information

([int] , [C,int,T])

- Type information can be declared for each bytecode instruction
- Type information **required** at the beginning of all **basic blocks**:
 - At jump target
 - At entry point of exception handler

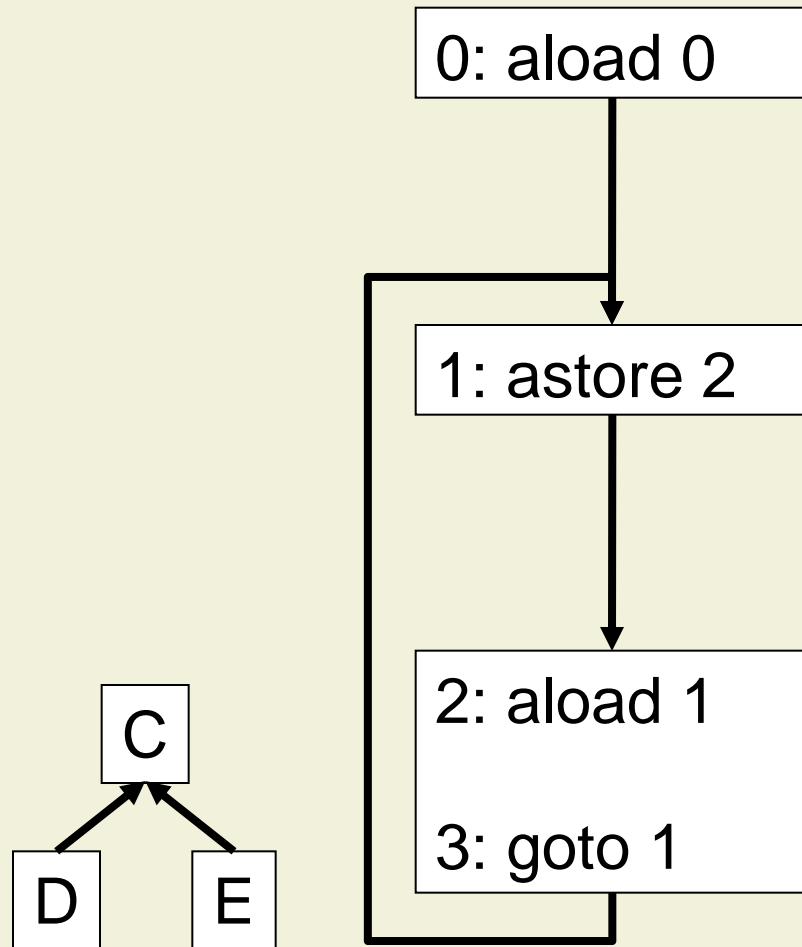
} Includes all join points
- Computation of SCS no longer necessary
 - Avoid fixpoint computation and interface problem

Type Checking Algorithm

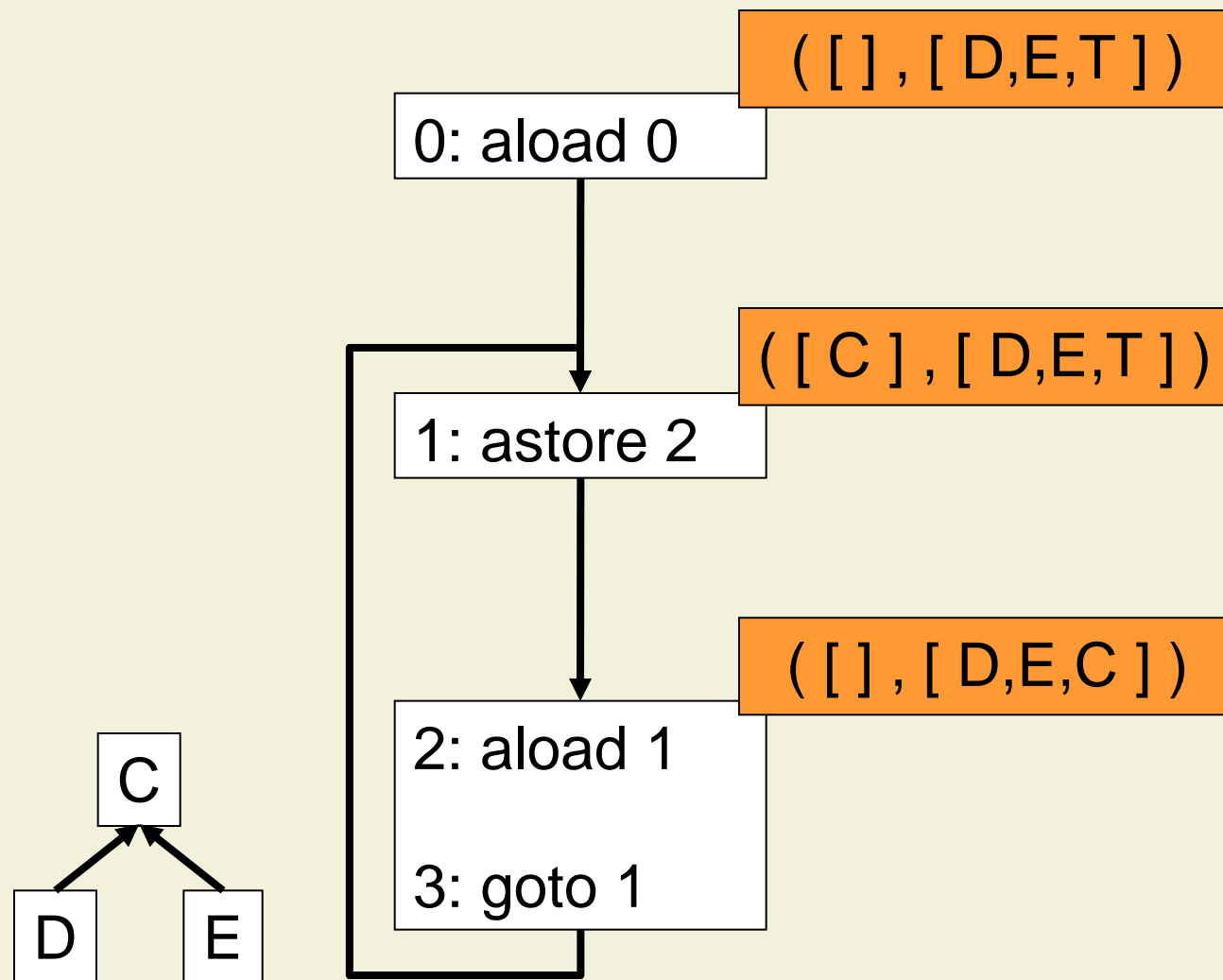
- Use and check declared types where available
- Infer types otherwise

```
foreach basic block of a method body do  
  foreach { i | instri is an instruction of basic block } do  
    if types( i ) is declared then in := types( i )  
    in := apply_rule( instri, in )  
    foreach q in successors( i ) do  
      if types( q ) is declared then  
        check that in is assignable to types( q )  
    end  
  end  
end
```

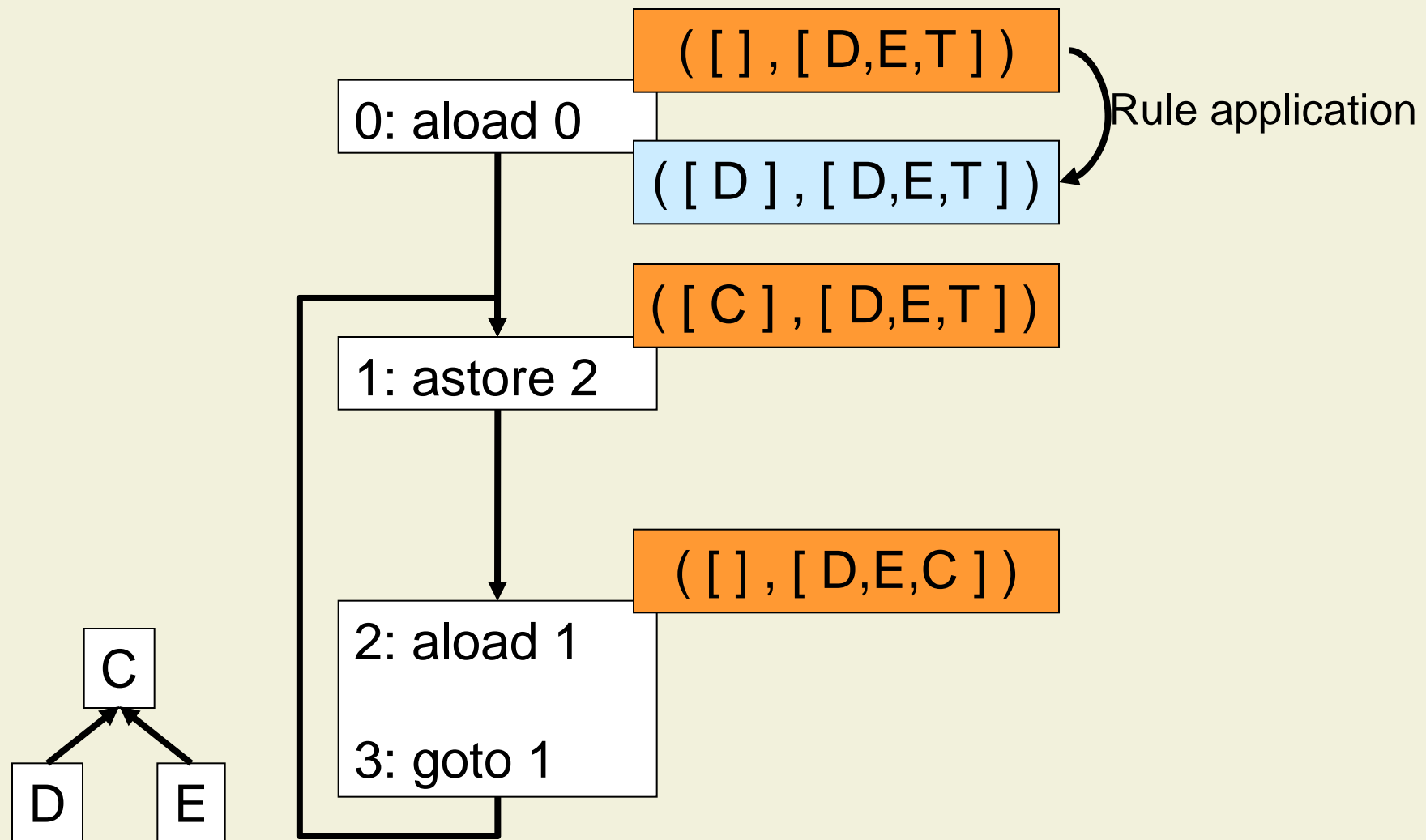
Type Checking Example



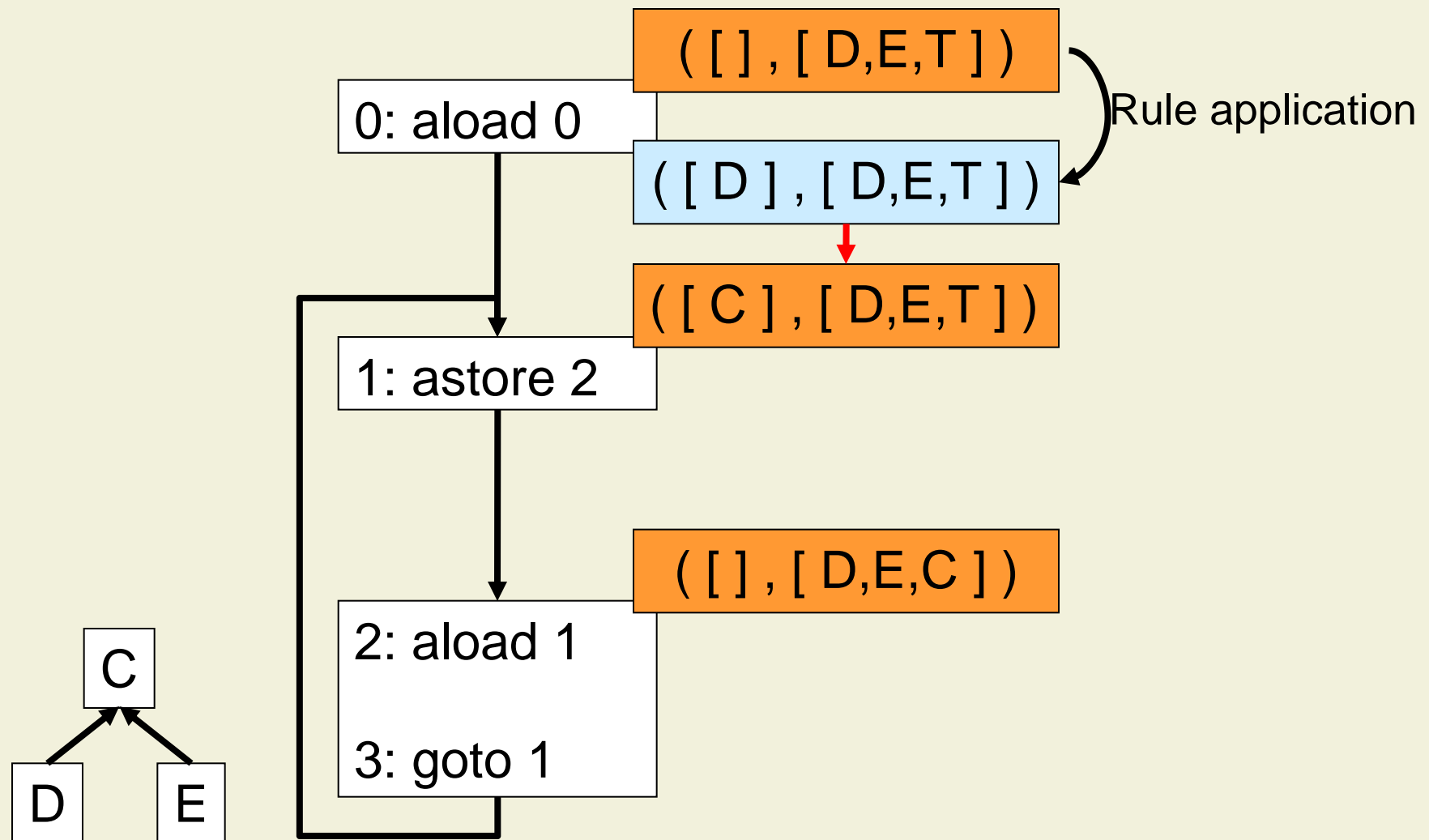
Type Checking Example



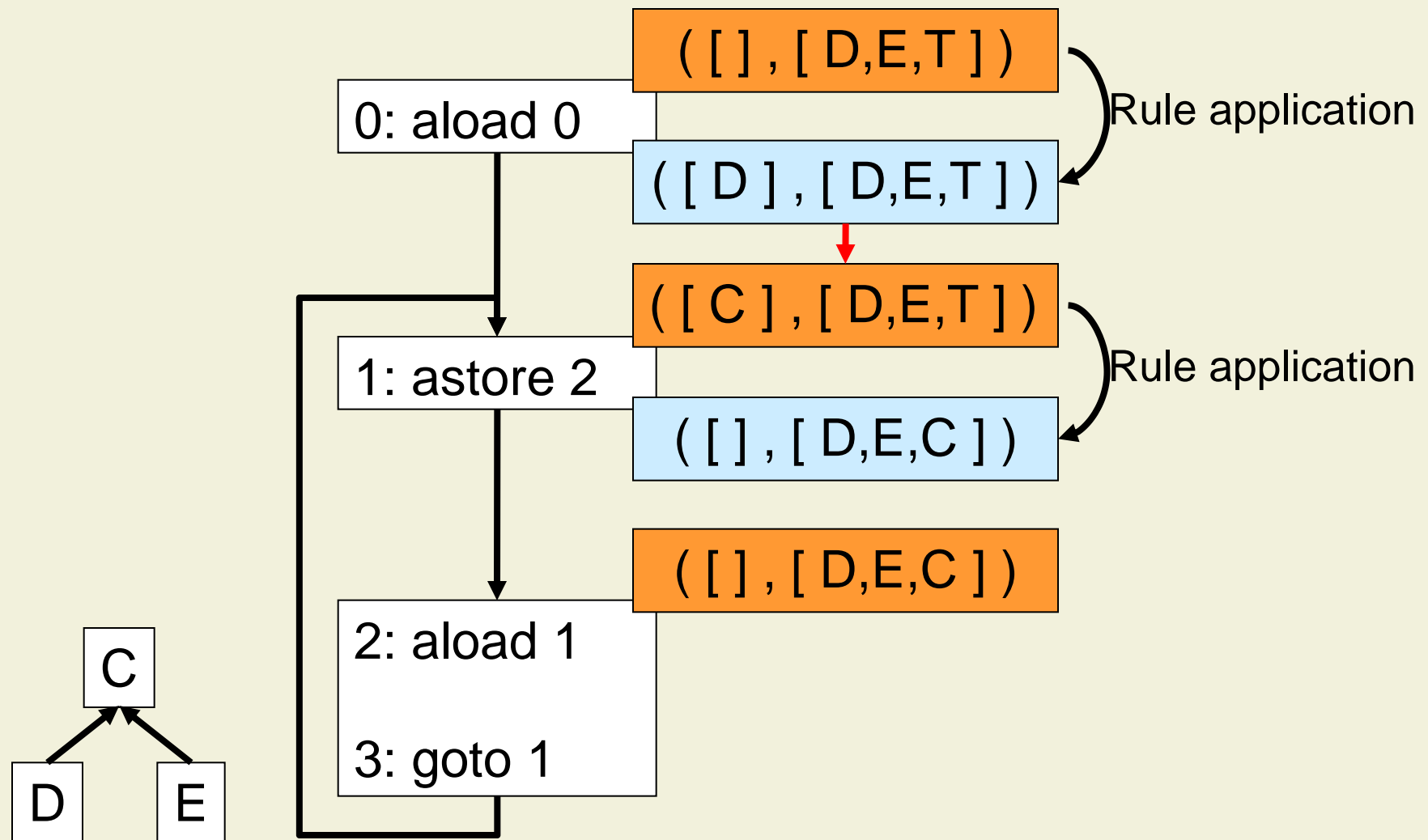
Type Checking Example



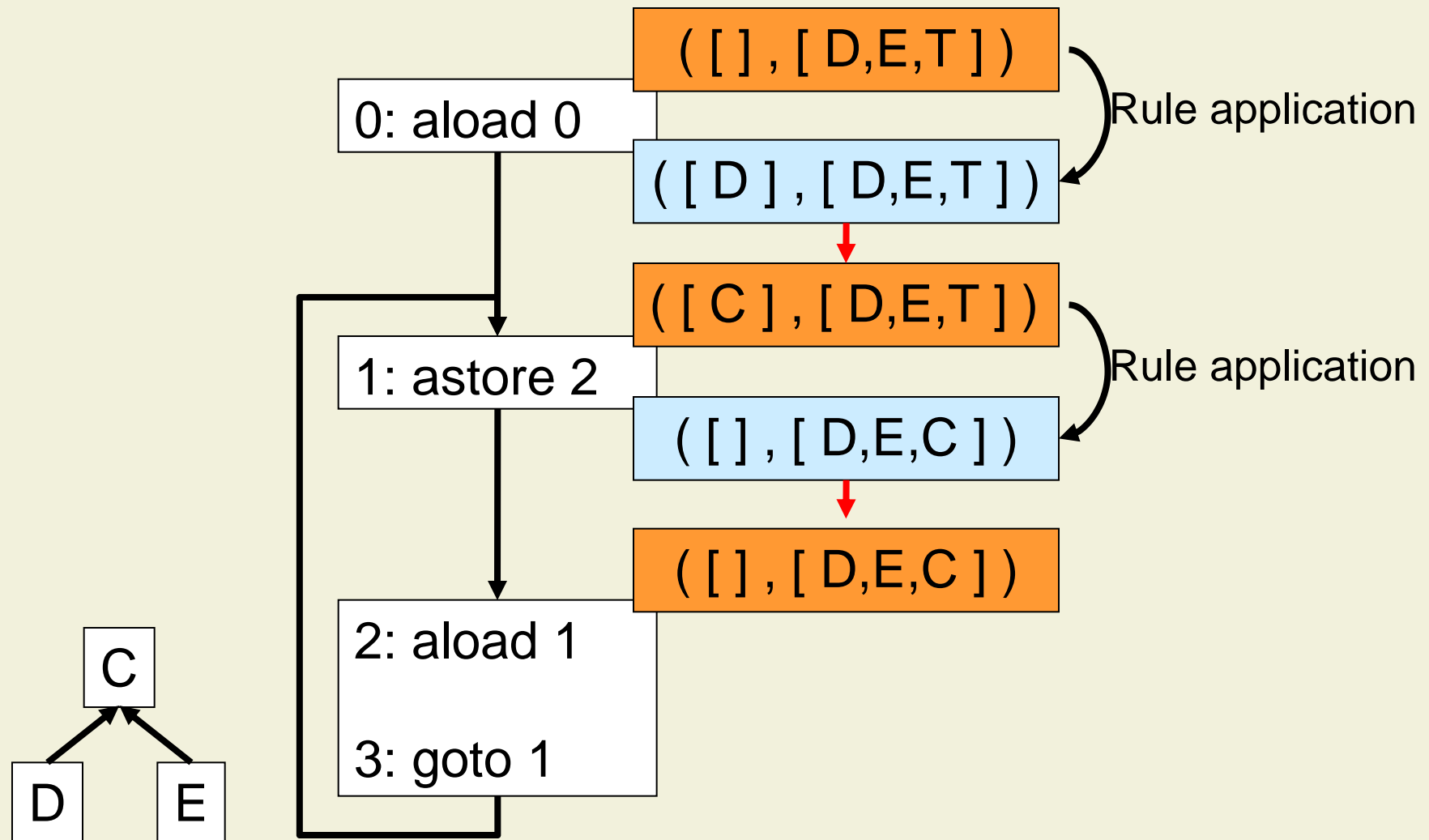
Type Checking Example



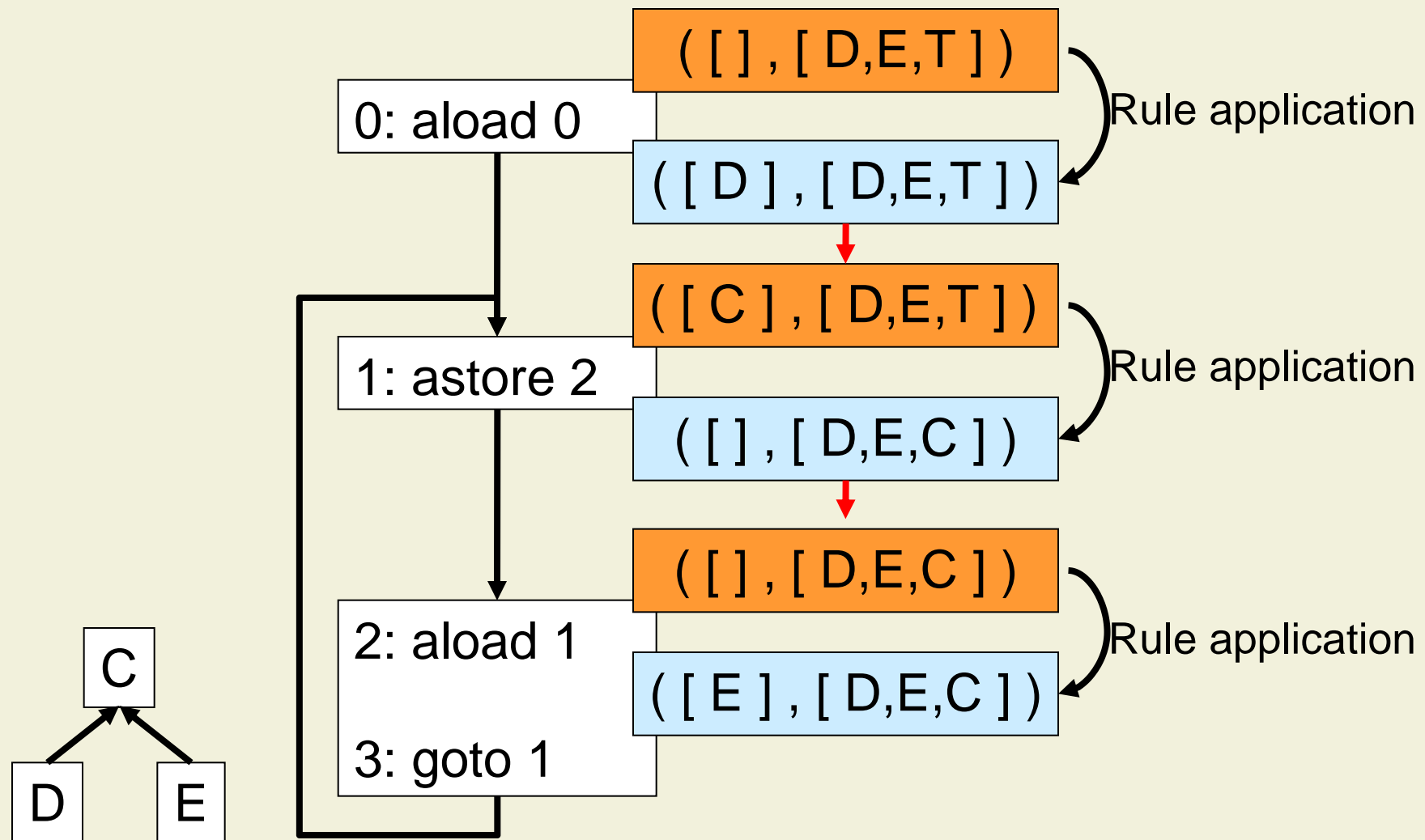
Type Checking Example



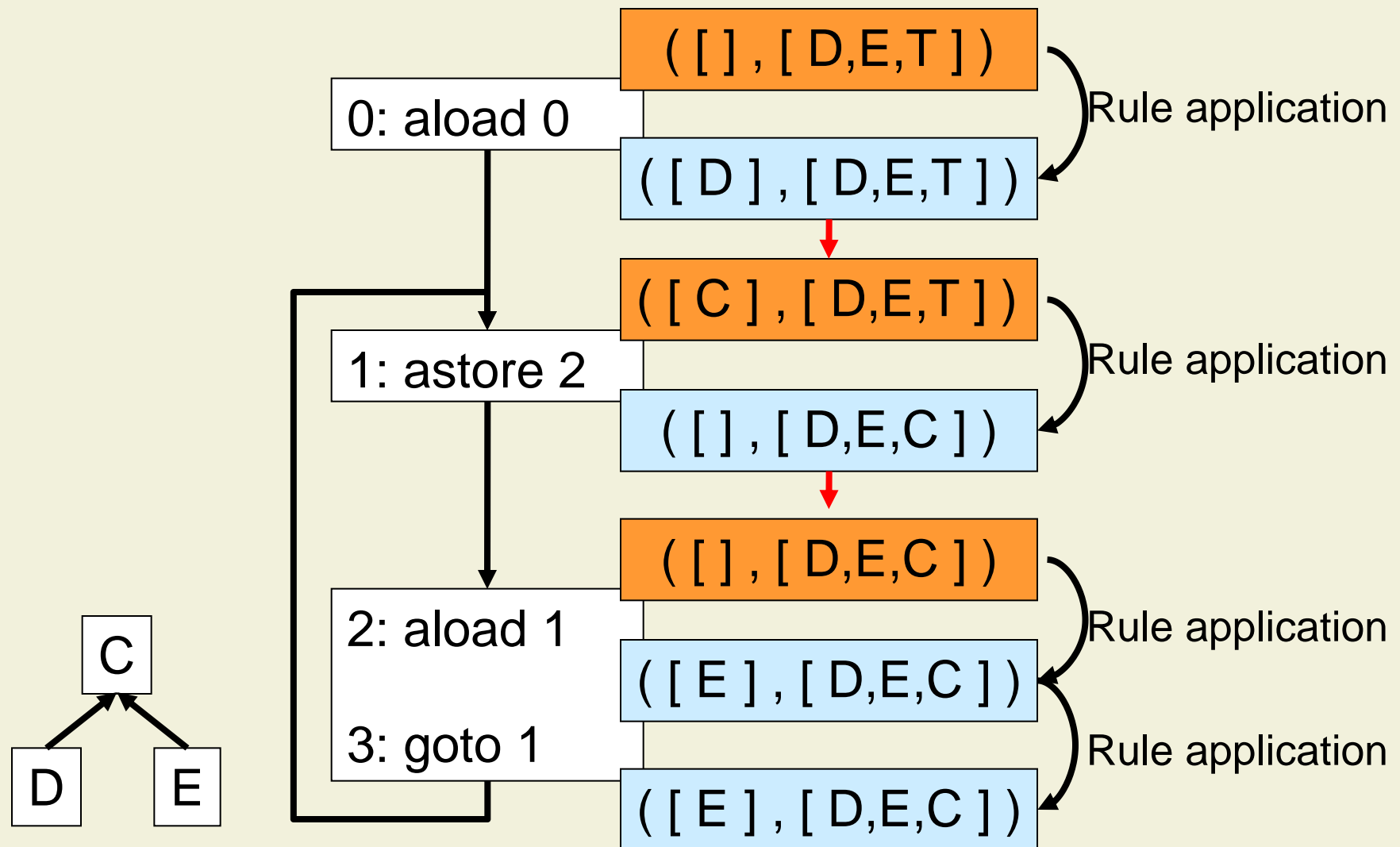
Type Checking Example



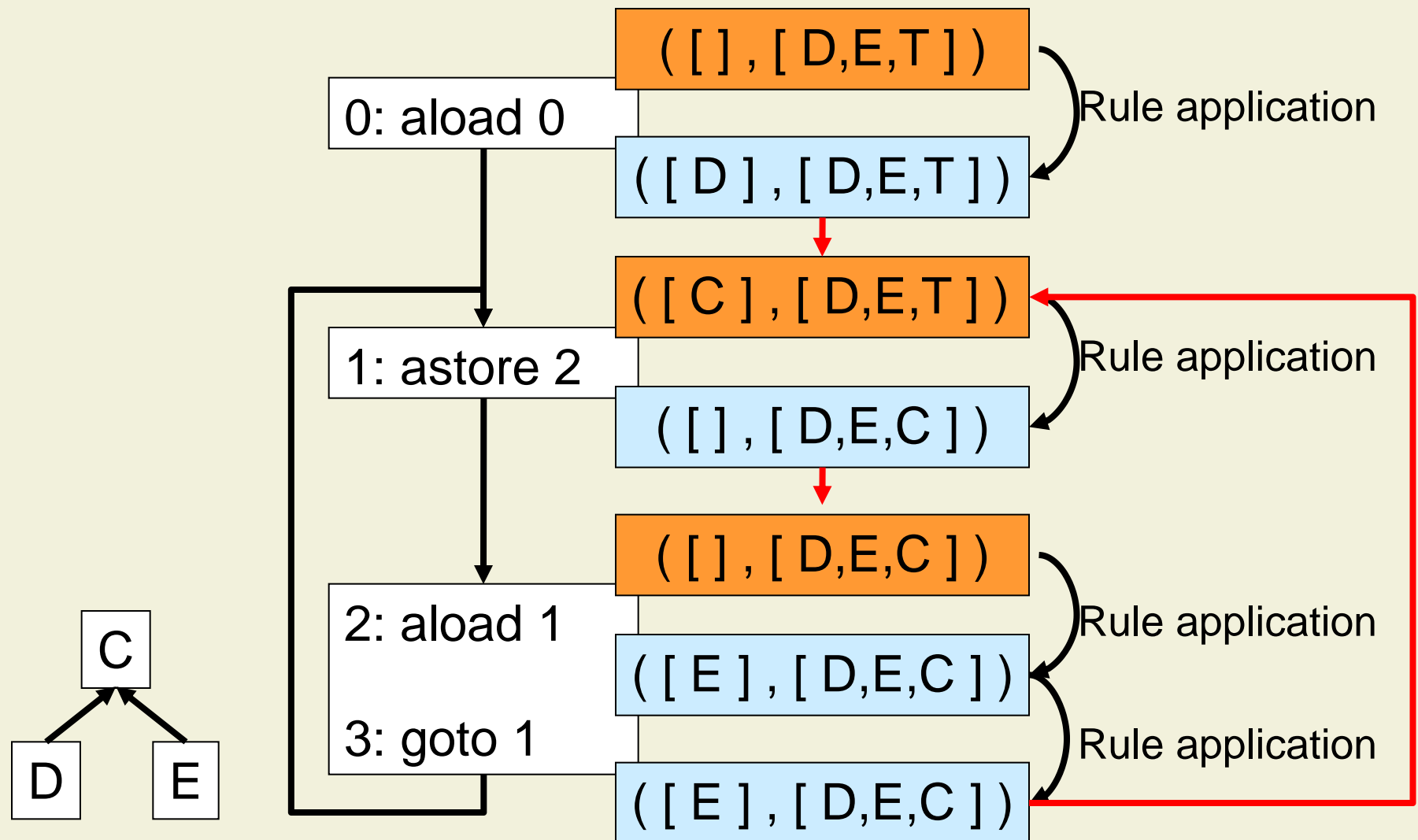
Type Checking Example



Type Checking Example



Type Checking Example



Bytecode Verification: Summary

- Bytecode verification enables secure mobile code
 - For programs written in typed bytecode
- Bytecode verification can be done via **type inference** or **type checking**
- Some run-time type checks are still necessary
 - For instance, casts and co-variant arrays

Type Inference for Source Programs

- Type inference can also be done on source code
 - For example, C# 3.0 and Scala **infer types of local variables**
 - **Reduce annotation overhead**, especially with generics

```
def sum( a: Array[ Int ] ): Int = {  
  val it = a.elements  
  var s = 0;  
  while( it.hasNext ) { s = s + it.next }  
  s  
}
```

Scala

Type Inference for Source Programs

- Type inference can also be done on source code
 - For example, C# 3.0 and Scala **infer types of local variables**
 - **Reduce annotation overhead**, especially with generics

```
def sum( a: Array[ Int ] ): Int = {  
  val it = a.elements  
  var s = 0;  
  while( it.hasNext ) { s = s + it.next }  
  s  
}
```

Scala

```
def client = {  
  var a = 1  
  a = "Hello"  
}
```

Scala

Type Inference for Source Programs

- Type inference can also be done on source code
 - For example, C# 3.0 and Scala **infer types of local variables**
 - **Reduce annotation overhead**, especially with generics
- Type annotations can still be used to support inference

```
def sum( a: Array[ Int ] ): Int = {  
  val it = a.elements  
  var s = 0;  
  while( it.hasNext ) { s = s + it.next }  
  s  
}
```

Scala

```
def client = {  
  var a = 1  
  a = "Hello"  
}
```

Scala

```
def client = {  
  var a: Any = 1  
  a = "Hello"  
}
```

Scala

Type Inference vs. Dynamic Typing

- Type inference determines the static type automatically and then performs static type checking
- Dynamic typing does not require a static type and does not perform static type checking

```
void client( ) {  
    var a = 1;  
    a = "Hello";  
}
```

C#

```
void client( ) {  
    dynamic a = 1;  
    a = "Hello";  
}
```

C#

Inference of Method and Field Types

- Inference of method signatures generally requires knowledge of all implementations
- Inference of field types generally requires knowledge of all accesses to the field
- Inference of these types is non-modular
 - Or based on speculation

```
class A {  
  var f = 5;  
  def foo( p: Int ) = {  
    p  
  }  
}
```

Scala

Inference of Method and Field Types

- Inference of method signatures generally requires knowledge of all implementations
- Inference of field types generally requires knowledge of all accesses to the field
- Inference of these types is non-modular
 - Or based on speculation

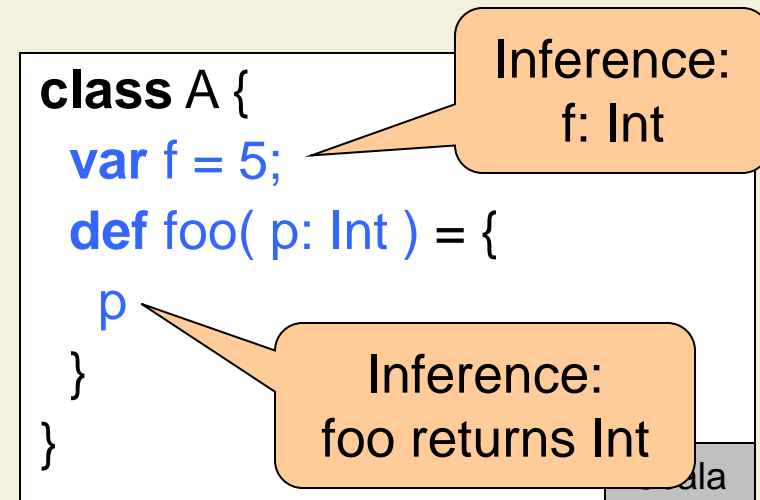
```
class A {  
  var f = 5;  
  def foo( p: Int ) = {  
    p  
  }  
}
```

Inference:
f: Int

Scala

Inference of Method and Field Types

- Inference of method signatures generally requires knowledge of all implementations
- Inference of field types generally requires knowledge of all accesses to the field
- Inference of these types is non-modular
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Inference of Method and Field Types

- Inference of method signatures generally requires knowledge of all implementations
- Inference of field types generally requires knowledge of all accesses to the field
- Inference of these types is non-modular
 - Or based on speculation

```
class A {  
  var f = 5;  
  def foo( p: Int ) = {  
    p  
  }  
}
```

Inference: f: Int

Inference: foo returns Int

Scala

```
class B extends A {  
  f = "Hello";  
  override def foo( p: Int ) = {  
    "Hello"  
  }  
}
```

Scala

4. Types

4.1 Bytecode Verification

4.2 Parametric Polymorphism

Polymorphism Revisited

- Not all polymorphic code is best expressed using subtype polymorphism
- Recovering precise type information requires **downcasts**

```
class Queue {  
    Object elem;  
    Queue next;  
    void enqueue( Object e ) { ... }  
    Object dequeue( ) { ... }  
}
```

Java

```
Queue q = new Queue( );  
String s = "Hello";  
q.enqueue( s );  
String t = ( String ) q.dequeue( );
```

Java

Polymorphism Revisited

- Not all polymorphic code is best expressed using subtype polymorphism
- Recovering precise type information requires **downcasts**
- Subtype relations are sometimes **not desirable**
 - E.g., covariant arrays

```
class Queue {  
    Object elem;  
    Queue next;  
    void enqueue( Object e ) { ... }  
    Object dequeue( ) { ... }  
}
```

Java

```
Queue q = new Queue( );  
String s = "Hello";  
q.enqueue( s );  
String t = ( String ) q.dequeue( );
```

Java

```
static void fill( Object[ ] a, Object val )  
{ ... }
```

Java

Parametric Polymorphism

- Classes and methods can be **parameterized with types**
- Clients provide instantiations for type parameters
- **Modularity**: generic code is type checked once and for all (without knowing the instantiations)

```
class Queue<T> {  
    T elem;  
    Queue<T> next;  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

Java

```
Queue<String> q;  
q = new Queue<String>( );  
String s = "Hello";  
q.enqueue( s );  
String t = q.dequeue( );
```

Java

```
static <T> void fill( T[ ] a, T val )  
{ ... }
```

Java

Type Checking Generic Code

- Type checking a generic class often **requires information about its type arguments**
 - Availability of methods
- Constraints can be expressed by specifying **upper bounds** on type parameters

```
class Queue<T> {  
    T elem;  
    Queue<T> next;  
  
    void enqueue( T e ) {  
        if( next == null ) { ... }  
        else {  
            if( e.compareTo( elem ) <= 0 ) {  
                next.enqueue( elem );  
                elem = e;  
            } else next.enqueue( e );  
        }  
    }  
    ...  
}
```

Java

Upper Bounds: Example

```
interface Comparable<T> {  
    int compareTo( T o );  
}
```

Java

```
class Queue<T extends Comparable<T>> {  
    T elem;  
    Queue<T> next;  
  
    void enqueue( T e ) {  
        if( next == null ) { ... }  
        else {  
            if( e.compareTo( elem ) <= 0 ) {  
                next.enqueue( elem );  
                elem = e;  
            } else next.enqueue( e );  
        }  
    }  
    ...  
}
```

Java

Upper Bounds: Example

```
interface Comparable<T> {  
    int compareTo( T o );  
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Java

```
class Queue<T extends Comparable<T>> {  
    T elem;  
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    void enqueue( T e ) {  
        if( next == null ) { ..  
        else {  
            if( e.compareTo( elem ) <= 0 ) {  
                next.enqueue( elem );  
                elem = e;  
            } else next.enqueue( e );  
        }  
    }  
    ...  
}
```

Typecheck under the
assumption
 $T \leq \text{Comparable}\langle T \rangle$

Java

Upper Bounds: Example

```
interface Comparable<T> {
    int compareTo( T o );
}
```

Java

```
Queue<String> q;
// String implements
    Comparable<String>
```

Java

```
class Queue<T extends Comparable<T>> {
    T elem;
    Queue<T> next;

    void enqueue( T e ) {
        if( next == null ) { ...
        else {
            if( e.compareTo( elem ) <= 0 ) {
                next.enqueue( elem );
                elem = e;
            } else next.enqueue( e );
        }
    }
    ...
}
```

Typecheck under the
assumption
 $T \leq \text{Comparable} \langle T \rangle$

Java

Upper Bounds: Example

```
interface Comparable<T> {
    int compareTo( T o );
}
```

Java

```
Queue<String> q;
// String implements
// Comparable<String>
```

Java

```
Queue<Person> q;
// Person does not
// implement
// Comparable<Person>
```

Java

```
class Queue<T extends Comparable<T>> {
    T elem;
    Queue<T> next;

    void enqueue( T e ) {
        if( next == null ) { ...
        else {
            if( e.compareTo( elem ) <= 0 ) {
                next.enqueue( elem );
                elem = e;
            } else next.enqueue( e );
        }
    }
    ...
}
```

Typecheck under the
assumption
 $T \leq \text{Comparable}\langle T \rangle$

Java

Subtyping and Generics

```
class Queue<T extends Comparable<T>> { ... }
```

Subtyping and Generics

```
class Queue<T extends Comparable<T>> { ... }
```

- Generic types are subtypes of their declared supertypes

```
Object o = new Queue<String>( );
```

Subtyping and Generics

```
class Queue<T extends Comparable<T>> { ... }
```

- Generic types are subtypes of their declared supertypes
- Type variables are subtypes of their upper bounds

```
Object o = new Queue<String>( );
```

```
void foo( T p ) {  
    Comparable<T> v = p;  
}
```

Subtyping and Generics

```
class Queue<T extends Comparable<T>> { ... }
```

- Generic types are subtypes of their declared supertypes
- Type variables are subtypes of their upper bounds
- How about different instantiations of the same generic class?

```
Object o = new Queue<String>( );
```

```
void foo( T p ) {  
    Comparable<T> v = p;  
}
```

```
List<Person> o;  
o = new List<Student>( );  
o = new List<Object>( );
```

Covariant Type Arguments

- Covariance:
If $S <: T$ then
 $C<S> <: C<T>$

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

Covariant Type Arguments

- Covariance:
If $S <: T$ then
 $C<S> <: C<T>$

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

```
void put( Queue<Object> q ) {  
    q.enqueue( "Hello" );  
}
```

Covariant Type Arguments

- Covariance:
If $S <: T$ then
 $C<S> <: C<T>$

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

```
void put( Queue<Object> q ) {  
    q.enqueue( "Hello" );  
}
```

Not type safe if q had
type Queue<Integer>

Covariant Type Arguments

- Covariance:
If $S <: T$ then
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```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

```
void put( Queue<Object> q ) {  
    q.enqueue( "Hello" );  
}
```

Not type safe if q had
type Queue<Integer>

```
Object get( Queue<Object> q ) {  
    return q.dequeue( );  
}
```

Covariant Type Arguments

- Covariance:
If $S <: T$ then
 $C<S> <: C<T>$
- Covariance is unsafe
when a generic type
argument is used for
variables that are
written by clients
 - Mutable fields
 - Method arguments

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

```
void put( Queue<Object> q ) {  
    q.enqueue( "Hello" );  
}
```

Not type safe if q had
type Queue<Integer>

```
Object get( Queue<Object> q ) {  
    return q.dequeue( );  
}
```

Contravariant Type Arguments

- Contravariance:
If $S <: T$ then
 $C<T> <: C<S>$

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

Contravariant Type Arguments

- Contravariance:
If $S <: T$ then
 $C<T> <: C<S>$

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

```
void put( Queue<String> q ) {  
    q.enqueue( "Hello" );  
}
```

Contravariant Type Arguments

- Contravariance:
If $S <: T$ then
 $C<T> <: C<S>$

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

```
void put( Queue<String> q ) {  
    q.enqueue( "Hello" );  
}
```

```
String get( Queue<String> q ) {  
    return q.dequeue( );  
}
```

Contravariant Type Arguments

- Contravariance:
If $S <: T$ then
 $C<T> <: C<S>$

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

```
void put( Queue<String> q ) {  
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}
```

```
String get( Queue<String> q ) {  
    return q.dequeue( );  
}
```

Not type safe if q had
type Queue<Object>

Contravariant Type Arguments

- Contravariance:
If $S <: T$ then
 $C<T> <: C<S>$
- Contravariance is unsafe when a generic type argument is used for variables that are read by clients
 - Fields
 - Method results

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

```
void put( Queue<String> q ) {  
    q.enqueue( "Hello" );  
}
```

```
String get( Queue<String> q ) {  
    return q.dequeue( );  
}
```

Not type safe if q had
type Queue<Object>

Java Solution: Non-Variance

- Generic types in Java are **non-variant** (neither covariant nor contravariant)
- Non-variance is **statically type safe**
 - No run-time checks needed

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

Java

```
Queue<Object> o;  
o = new Queue<String>( );
```

Java

```
Queue<String> o;  
o = new Queue<Object>( );
```

Java

Java Solution: Non-Variance

- Generic types in Java are **non-variant** (neither covariant nor contravariant)
- Non-variance is **statically type safe**
 - No run-time checks needed
- Non-variance is sometimes overly restrictive

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

Java

```
Queue<Object> o;  
o = new Queue<String>( );
```

Java

```
Queue<String> o;  
o = new Queue<Object>( );
```

Java

```
class Random<T> {  
    T next( ) { ... }  
}
```

Java: Generics vs. Arrays

- Recall: Java/C# arrays are covariant
- But an array `T[]` is not much different from a class `Array<T>`

```
Object[ ] o;  
o = new String[ 5 ];
```

Java

```
Queue<Object> o;  
o = new Queue<String>( );
```

Java

Java: Generics vs. Arrays

- Recall: Java/C# arrays are covariant
- But an array `T[]` is not much different from a class `Array<T>`
- Run-time checks
 - Covariant arrays require run-time checks for each update
 - Covariant generics would need checks for field updates and argument passing
- Covariant generics would require more run-time checks in more bytecode instructions

```
Object[ ] o;  
o = new String[ 5 ];
```

Java

```
Queue<Object> o;  
o = new Queue<String>( );
```

Java

Scala Solution: Variance Annotations

- By default, generic types in Scala are **non-variant**

```
class Queue[T] {  
  def enqueue( e: T ) = { ... }  
  def dequeue: T = { ... }  
}
```

Scala

```
Queue[ AnyRef ] o;  
o = new Queue[ String ]( );
```

Scala

```
Queue[ String ] o;  
o = new Queue[ AnyRef ]( );
```

Scala

Scala Solution: Variance Annotations

- By default, generic types in Scala are **non-variant**
- Programmers can supply **variance annotations** to allow **co-** and **contravariance**

```
class Queue[T] {  
  def enqueue( e: T ) = { ... }  
  def dequeue: T = { ... }  
}
```

Scala

```
Queue[ AnyRef ] o;  
o = new Queue[ String ]( );
```

Scala

```
Queue[ String ] o;  
o = new Queue[ AnyRef ]( );
```

Scala

Scala Solution: Variance Annotations

- By default, generic types in Scala are **non-variant**
- Programmers can supply **variance annotations** to allow **co-** and **contravariance**
- Type checker imposes **restrictions** on use of variance annotations

```
class Queue[T] {  
  def enqueue( e: T ) = { ... }  
  def dequeue: T = { ... }  
}
```

Scala

```
Queue[ AnyRef ] o;  
o = new Queue[ String ]( );
```

Scala

```
Queue[ String ] o;  
o = new Queue[ AnyRef ]( );
```

Scala

Covariance Annotations

- A covariance annotation (+) is useful when type variable occurs **only in positive positions**
 - Result type
 - Types of immutable fields

```
class Random[ +T ] {  
  def next: T = { ... }  
}
```

Scala

```
val r: Random[ AnyRef ] =  
    new Random[ String ]( )  
val a = r.next
```

Scala

Covariance Annotations

- A covariance annotation (+) is useful when type variable occurs **only in positive positions**

- Result type
- Types of immutable fields

- Type checker prevents other occurrences

```
class Random[ +T ] {  
  def next: T = { ... }  
}
```

Scala

```
val r: Random[ AnyRef ] =  
    new Random[ String ]()  
val a = r.next
```

Scala

```
class Random[ +T ] {  
  def next: T = { ... }  
  def initialize( i: T ) = { ... }  
}
```

Scala

Contravariance Annotations

- A contravariance annotation (-) is useful when type variable occurs **only in negative positions**
 - Parameter type

```
class OutputChannel[ -T ] {  
  def write( x: T ) = { ... }  
}
```

Scala

```
val o: OutputChannel[ String ] =  
  new OutputChannel[ AnyRef ]( )  
o.write( "Hello" )
```

Scala

Contravariance Annotations

- A contravariance annotation (-) is useful when type variable occurs **only in negative positions**
 - Parameter type
- Type checker prevents other occurrences

```
class OutputChannel[ -T ] {  
  def write( x: T ) = { ... }  
}
```

Scala

```
val o: OutputChannel[ String ] =  
  new OutputChannel[ AnyRef ]( )  
o.write( "Hello" )
```

Scala

```
class OutputChannel[ -T ] {  
  def write( x: T ) = { ... }  
  def lastWritten: T = { ... }  
}
```

Scala

Working with Non-Variant Generics

- How can we write code that works with many different instantiations of a generic class?

Working with Non-Variant Generics

- How can we write code that works with many different instantiations of a generic class?
- Solution 1: Additional type parameters

```
static void printAll( Collection<Object> c ) {  
    for ( Object e : c ) { System.out.println( e ); }  
}
```

Java

```
foo( Collection<String> p ) {  
    printAll( p );  
}
```

Java

Working with Non-Variant Generics

- How can we write code that works with many different instantiations of a generic class?
- Solution 1: Additional type parameters

```
static void printAll( Collection<Object> c ) {  
    for ( Object e : c ) { System.out.println( e ); }  
}
```

Java

```
foo( Collection<String> p ) {  
    printAll( p );  
}
```

Java

```
static <T> void printAll( Collection<T> c ) {  
    for ( T e : c ) { System.out.println( e ); }  
}
```

Java

```
foo( Collection<String> p ) {  
    printAll( p );  
}
```

Java

Additional Type Parameters

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<E> {  
    TreeSet( Comparator<E> c ) { ... }  
    ... }
```

Additional Type Parameters

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<E> {  
    TreeSet( Comparator<E> c ) { ... }  
    ... }
```

TreeSet needs to
compare set elements

Additional Type Parameters

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<E> {  
    TreeSet( Comparator<E> c ) { ... }  
    ... }
```

TreeSet needs to
compare set elements

```
class Person { ... }
```

```
class Student extends Person { ... }
```

```
class PersonComp implements Comparator<Person> {  
    int compare( Person fst, Person snd ) { ... }  
}
```

Additional Type Parameters

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<E> {  
    TreeSet( Comparator<E> c ) { ... }  
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class PersonComp implements Comparator<Person> {  
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}
```

Universal comparator
for all persons

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interface Comparator<T> {  
    int compare( T fst, T snd );  
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```
class TreeSet<E> {  
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TreeSet needs to
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class Person { ... }
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class Student extends Person { ... }
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```
class PersonComp implements Comparator<Person> {  
    int compare( Person fst, Person snd ) { ... }  
}
```

Universal comparator
for all persons

```
TreeSet<Student> s = new TreeSet<Student>( new PersonComp() );
```

Additional Type Parameters

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<E> {  
    TreeSet( Comparator<E> c ) { ... }  
    ... }
```

TreeSet needs to
compare set elements

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class Person { ... }
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```
class Student extends Person { ... }
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Universal comparator
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class TreeSet<E> {  
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TreeSet needs to
compare set elements

```
class Person { ... }
```

```
class Student extends Person { ... }
```

```
class PersonComp implements Comparator<Person> {  
    int compare( Person fst, Person snd ) { ... }  
}
```

Universal comparator
for all persons

```
TreeSet<Student> s = new TreeSet<Student>( new PersonComp() );
```

Compile-time error: PersonComp is not
a subtype of Comparator<Student>

Additional Type Parameters: Version 1

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<F, E extends F> {  
    TreeSet( Comparator<F> c ) { ... }  
    ... }
```

Additional Type Parameters: Version 1

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<F, E extends F> {  
    TreeSet( Comparator<F> c ) { ... }  
    ... }
```

Comparator can
compare at least Es

Additional Type Parameters: Version 1

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<F, E extends F> {  
    TreeSet( Comparator<F> c ) { ... }  
    ... }
```

Comparator can
compare at least Es

```
TreeSet<Person, Student> s =  
    new TreeSet<Person, Student>( new PersonComp() );
```

Additional Type Parameters: Version 1

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<F, E extends F> {  
    TreeSet( Comparator<F> c ) { ... }  
    ... }
```

Comparator can
compare at least Es

```
TreeSet<Person, Student> s =  
    new TreeSet<Person, Student>( new PersonComp() );
```

■ Drawbacks

- Additional type argument is a nuisance for clients and reveals implementation details
- Type-instantiation of Comparator cannot be changed at run time, for instance, to Comparator<Object>

Additional Type Parameters: Version 2

```
class TreeSet<E> {  
    TreeSet( Comparator<E> c ) { ... }  
    ... }
```

Additional Type Parameters: Version 2

```
class TreeSet<E> {  
    TreeSet( Comparator<E> c ) { ... }  
    ... }
```

```
class PersonComp<T extends Person> implements Comparator<T> {  
    int compare( T fst, T snd ) { ... }  
}
```

PersonComp can
compare different
kinds of Persons

Additional Type Parameters: Version 2

```
class TreeSet<E> {  
    TreeSet( Comparator<E> c ) { ... }  
    ... }
```

```
class PersonComp<T extends Person> implements Comparator<T> {  
    int compare( T fst, T snd ) { ... }  
}
```

PersonComp can
compare different
kinds of Persons

```
TreeSet<Student> s =  
    new TreeSet<Student>( new PersonComp<Student>() );
```

Additional Type Parameters: Version 2

```
class TreeSet<E> {  
    TreeSet( Comparator<E> c ) { ... }  
    ... }
```

```
class PersonComp<T extends Person> implements Comparator<T> {  
    int compare( T fst, T snd ) { ... }  
}
```

PersonComp can
compare different
kinds of Persons

```
TreeSet<Student> s =  
    new TreeSet<Student>( new PersonComp<Student>() );
```

■ Drawback

- Additional type argument is a nuisance for clients
- Design of PersonComp requires foresight

Solution 2: Wildcards

- A wildcard represents an **unknown type**

```
static <T> void printAll( Collection<T> c ) {  
    for ( T e : c ) { System.out.println( e ); }  
}
```

Java

```
static void printAll( Collection<?> c ) {  
    for ( Object e : c ) { System.out.println( e ); }  
}
```

Java

Wildcards and Existential Types

```
static void printAll( Collection<?> c ) {  
    for ( Object e : c ) { System.out.println( e ); }  
}
```

Java

- Interpretation as **existential type**
 - “There exists a type argument T such that c has type Collection<T>”
 - Existential quantifier is instantiated automatically by the type system

```
Collection<String> c = new ArrayList<String>( );  
...  
printAll( c );
```

Java

Wildcards and Existential Types

```
static void printAll( Collection<?> c ) {  
    for ( Object e : c ) { System.out.println( e ); }  
}
```

Java

- Interpretation as **existential type**
 - “There exists a type argument T such that c has type Collection<T>”
 - Existential quantifier is instantiated automatically by the type system

```
Collection<String> c = new ArrayList<String>( );  
...  
printAll( c );
```

Java

Wildcard instantiated
with String

Wildcard Examples

```
static Collection<?> id( Collection<?> c ) {  
    return c;  
}
```

Wildcard Examples

```
static Collection<?> id( Collection<?> c ) {  
    return c;  
}
```

Two existential
types

Wildcard Examples

Correct: type checker
instantiates type argument
with c's type argument

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static Collection<?> id( Collection<?> c ) {  
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Two existential
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Wildcard Examples

Correct: type checker
instantiates type argument
with c's type argument

```
static Collection<?> id( Collection<?> c ) {  
    return c;  
}
```

Two existential
types

```
Collection<String> c = new ArrayList<String>( );  
Collection<String> d = id( c );
```

Wildcard Examples

Correct: type checker
instantiates type argument
with c's type argument

```
static Collection<?> id( Collection<?> c ) {  
    return c;  
}
```

Two existential
types

```
Collection<String> c = new ArrayList<String>( );  
Collection<String> d = id( c );
```

Type error: existential
types might have
different instantiations
(modular type checking)

Wildcard Examples (cont'd)

```
static void merge( Collection<?> c, Collection<?> d ) {  
    for( Object e : c ) { d.add( e ); }  
}
```

Wildcard Examples (cont'd)

```
static void merge( Collection<?> c, Collection<?> d ) {  
    for( Object e : c ) { d.add( e ); }  
}
```

Two existential
types

Wildcard Examples (cont'd)

```
static void merge( Collection<?> c, Collection<?> d ) {  
    for( Object e : c ) { d.add( e ); }  
}
```

Two existential
types

Type error: d might
expect elements of
different type

Wildcard Examples (cont'd)

```
class Spooler {  
    Collection<?> task;  
  
    void setTask( Collection<?> c ) {  
        task = c;  
    }  
    void print( ) {  
        for ( Object e : task ) { System.out.println( e ); }  
    }  
}
```

Wildcard Examples (cont'd)

```
class Spooler {  
    Collection<?> task;  
  
    void setTask( Collection<?> c ) {  
        task = c;  
    }  
  
    void print( ) {  
        for ( Object e : task ) { System.out.println( e ); }  
    }  
}
```

Correct: type checker
instantiates task's type
argument with c's

Wildcard Examples (cont'd)

```
class Spooler {  
    Collection<?> task;  
  
    void setTask( Collection<?> c ) {  
        task = c;  
    }  
  
    void print( ) {  
        for ( Object e : task ) { System.out.println( e ); }  
    }  
}
```

Cannot be simulated
with method type
parameters

Correct: type checker
instantiates task's type
argument with c's

Wildcard Examples (cont'd)

```
class Spooler {  
    Collection<?> task;  
  
    void setTask( Collection<?> c ) {  
        task = c;  
    }  
  
    void print( ) {  
        for ( Object e : task ) { System.out.println( e ); }  
    }  
}
```

Cannot be simulated
with method type
parameters

Correct: type checker
instantiates task's type
argument with c's

Works because
every Java object
has toString method

Constrained Wildcards

```
static void printFormatted( Collection<?> c ) {  
    for ( Object e : c ) {  
        String s = e.format( 80 );  
        System.out.println( s );  
    }  
}
```

Constrained Wildcards

```
static void printFormatted( Collection<?> c ) {  
    for ( Object e : c ) {  
        String s = e.format( 80 );  
        System.out.println( s );  
    }  
}
```

Type error: elements
might not support
method format

Constrained Wildcards: Upper Bounds

```
interface Format {  
    String format( int width );  
}
```

```
static void printFormatted( Collection<? extends Format> c ) {  
    for ( Format e : c ) {  
        String s = e.format( 80 );  
        System.out.println( s );  
    }  
}
```

Constrained Wildcards: Upper Bounds

```
interface Format {  
    String format( int width );  
}
```

```
static void printFormatted( Collection<? extends Format> c ) {  
    for ( Format e : c ) {  
        String s = e.format( 80 );  
        System.out.println( s );  
    }  
}
```

Typecheck under the
assumption
? <: Format

Constrained Wildcards: Upper Bounds

```
interface Format {  
    String format( int width );  
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```
static void printFormatted( Collection<? extends Format> c ) {  
    for ( Format e : c ) {  
        String s = e.format( 80 );  
        System.out.println( s );  
    }  
}
```

Typecheck under the
assumption
? <: Format

```
Collection<Object> c = new ArrayList<Object>( );  
printFormatted( c );
```

Constrained Wildcards: Upper Bounds

```
interface Format {  
    String format( int width );  
}
```

```
static void printFormatted( Collection<? extends Format> c ) {  
    for ( Format e : c ) {  
        String s = e.format( 80 );  
        System.out.println( s );  
    }  
}
```

Typecheck under the
assumption
 $? <: \text{Format}$

```
Collection<Object> c = new ArrayList<Object>( );  
printFormatted( c );
```

Compile-time error:
Object is not a subtype of
the upper bound Format

More Bounded Wildcards

```
class Cell<T> {  
    T value;  
  
    void copyFromT( Cell<T> other ) {  
        value = other.value;  
    }  
  
}
```

More Bounded Wildcards

```
class Cell<T> {  
    T value;  
  
    void copyFromT( Cell<T> other ) {  
        value = other.value;  
    }  
  
}
```

Overly
restrictive

More Bounded Wildcards

```
class Cell<T> {  
    T value;  
  
    void copyFromT( Cell<T> other ) {  
        value = other.value;  
    }  
  
    void copyFrom( Cell<?> other ) {  
        value = other.value;  
    }  
  
}
```

More Bounded Wildcards

```
class Cell<T> {  
    T value;  
  
    void copyFromT( Cell<T> other ) {  
        value = other.value;  
    }  
  
    void copyFrom( Cell<?> other ) {  
        value = other.value;  
    }  
}
```

Not type
correct

More Bounded Wildcards

```
class Cell<T> {  
    T value;  
  
    void copyFromT( Cell<T> other ) {  
        value = other.value;  
    }  
  
    void copyFrom( Cell<? extends T> other ) {  
        value = other.value;  
    }  
  
}
```

More Bounded Wildcards

Typecheck under
the assumption

$? \leq T$

```
class Cell<T> {  
    T value;  
  
    void copyFromT( Cell<T> other ) {  
        value = other.value;  
    }  
  
    void copyFrom( Cell<? extends T> other ) {  
        value = other.value;  
    }  
}
```

More Bounded Wildcards

Typecheck under
the assumption

$? \leq T$

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class Cell<T> {  
    T value;  
  
    void copyFromT( Cell<T> other ) {  
        value = other.value;  
    }  
  
    void copyFrom( Cell<? extends T> other ) {  
        value = other.value;  
    }  
  
    void copyTo( Cell<?> other ) {  
        other.value = value;  
    }  
}
```

More Bounded Wildcards

```
class Cell<T> {  
    T value;  
  
    void copyFromT( Cell<T> other ) {  
        value = other.value;  
    }  
  
    void copyFrom( Cell<? extends T> other ) {  
        value = other.value;  
    }  
  
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        other.value = value;  
    }  
}
```

Typecheck under
the assumption

$? <: T$

Not type
correct

More Bounded Wildcards

```
class Cell<T> {  
    T value;  
  
    void copyFromT( Cell<T> other ) {  
        value = other.value;  
    }  
  
    void copyFrom( Cell<? extends T> other ) {  
        value = other.value;  
    }  
  
    void copyTo( Cell<? super T> other ) {  
        other.value = value;  
    }  
}
```

Typecheck under
the assumption

? <: T

Wildcard can
also have
lower bounds

More Bounded Wildcards

```
class Cell<T> {  
    T value;  
  
    void copyFromT( Cell<T> other ) {  
        value = other.value;  
    }  
  
    void copyFrom( Cell<? extends T> other ) {  
        value = other.value;  
    }  
  
    void copyTo( Cell<? super T> other ) {  
        other.value = value;  
    }  
}
```

Typecheck under
the assumption

? <: T

Typecheck under
the assumption

T <: ?

Wildcard can
also have
lower bounds

Use-Site Variance: Covariance

- Wildcards allow clients to decide on variance at the use site
 - As opposed to Scala's declaration-site variance

```
class Random<T> {  
    T next( ) { ... }  
  
}
```

Java

```
Random<? extends Person> r =  
    new Random<Student>( );  
Person a = r.next( );
```

Use-Site Variance: Covariance

- Wildcards allow clients to decide on variance at the use site
 - As opposed to Scala's declaration-site variance

```
class Random<T> {  
  T next( ) { ... }  
}
```

Java

Upper bound permits
covariant instantiation

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Random<? extends Person> r =  
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Covariant uses
typecheck

Use-Site Variance: Covariance

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class Random<T> {  
  T next( ) { ... }  
  void initialize( T i ) { ... }  
}
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Java

Upper bound permits
covariant instantiation

```
Random<? extends Person> r =  
    new Random<Student>( );  
Person a = r.next( );
```

Covariant uses
typecheck

```
r.initialize( new Student( ) );
```

Use-Site Variance: Covariance

- Wildcards allow clients to decide on variance at the use site
 - As opposed to Scala's declaration-site variance

```
class Random<T> {  
  T next( ) { ... }  
  void initialize( T i ) { ... }  
}
```

Java

Upper bound permits
covariant instantiation

```
Random<? extends Person> r =  
    new Random<Student>( );  
Person a = r.next( );
```

Covariant uses
typecheck

```
r.initialize( new Student( ) );
```

Contravariant uses do
not typecheck

Use-Site Variance: Contravariance

```
class OutputChannel<T> {  
    void write( T x ) { ... }  
  
}
```

Java

```
OutputChannel<? super Student> o =  
    new OutputChannel<Person>( );  
o.write( new Student( ) );
```

Use-Site Variance: Contravariance

```
class OutputChannel<T> {  
  void write( T x ) { ... }  
}
```

Java

```
OutputChannel<? super Student> o =  
    new OutputChannel<Person>( );  
o.write( new Student( ) );
```

Lower bound permits
contravariant
instantiation

Use-Site Variance: Contravariance

```
class OutputChannel<T> {  
    void write( T x ) { ... }  
}
```

Java

```
OutputChannel<? super Student> o =  
    new OutputChannel<Person>( );  
o.write( new Student( ) );
```

Lower bound permits
contravariant
instantiation

Contravariant uses
typecheck

Use-Site Variance: Contravariance

```
class OutputChannel<T> {  
  void write( T x ) { ... }  
  T lastWritten( ) { ... }  
}
```

Java

```
OutputChannel<? super Student> o =  
    new OutputChannel<Person>( );  
o.write( new Student( ) );
```

Lower bound permits
contravariant
instantiation

Contravariant uses
typecheck

Use-Site Variance: Contravariance

```
class OutputChannel<T> {  
    void write( T x ) { ... }  
    T lastWritten( ) { ... }  
}
```

Java

```
OutputChannel<? super Student> o =  
    new OutputChannel<Person>( );  
o.write( new Student( ) );
```

Lower bound permits
contravariant
instantiation

Contravariant uses
typecheck

```
Person s = o.lastWritten( );
```

Use-Site Variance: Contravariance

```
class OutputChannel<T> {  
  void write( T x ) { ... }  
  T lastWritten( ) { ... }  
}
```

Java

```
OutputChannel<? super Student> o =  
  new OutputChannel<Person>( );  
o.write( new Student( ) );
```

Lower bound permits
contravariant
instantiation

Contravariant uses
typecheck

```
Person s = o.lastWritten( );
```

Covariant uses do not
typecheck

TreeSet Revisited

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<E> {  
    TreeSet( Comparator<? super E> c ) { ... }  
    ... }
```

```
class Person { ... }
```

```
class Student extends Person { ... }
```

```
class PersonComp implements Comparator<Person> {  
    int compare( Person fst, Person snd ) { ... }  
}
```

TreeSet Revisited

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<E> {  
    TreeSet( Comparator<? super E> c ) { ... }  
    ... }
```

TreeSet needs to compare
at least set elements
(use-site contravariance)

```
class Person { ... }
```

```
class Student extends Person { ... }
```

```
class PersonComp implements Comparator<Person> {  
    int compare( Person fst, Person snd ) { ... }  
}
```

TreeSet Revisited

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class TreeSet<E> {  
    TreeSet( Comparator<? super E> c ) { ... }  
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(use-site contravariance)

```
class Person { ... }
```

```
class Student extends Person { ... }
```

```
class PersonComp implements Comparator<Person> {  
    int compare( Person fst, Person snd ) { ... }  
}
```

```
TreeSet<Student> s = new TreeSet<Student>( new PersonComp() );
```

TreeSet Revisited

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<E> {  
    TreeSet( Comparator<? super E> c ) { ... }  
    ... }
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TreeSet needs to compare
at least set elements
(use-site contravariance)

```
class Person { ... }
```

```
class Student extends Person { ... }
```

```
class PersonComp implements Comparator<Person> {  
    int compare( Person fst, Person snd ) { ... }  
}
```

```
TreeSet<Student> s = new TreeSet<Student>( new PersonComp() );
```

TreeSet Revisited

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
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class TreeSet<E> {  
    TreeSet( Comparator<? super E> c ) { ... }  
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```

TreeSet needs to compare
at least set elements
(use-site contravariance)

```
class Person { ... }
```

```
class Student extends Person { ... }
```

```
class PersonComp implements Comparator<Person> {  
    int compare( Person fst, Person snd ) { ... }  
}
```

```
TreeSet<Student> s = new TreeSet<Student>( new PersonComp() );
```

Wildcard instantiated with Person,
which is a supertype of Student

Wildcards vs. Method Type Parameters

```
void copyFrom( Cell<? extends T> other ) {  
    value = other.value;  
}
```

```
<S extends T> void copyFrom( Cell<S> other ) {  
    value = other.value;  
}
```

Wildcards vs. Method Type Parameters

```
void copyFrom( Cell<? extends T> other ) {  
    value = other.value;  
}
```

```
<S extends T> void copyFrom( Cell<S> other ) {  
    value = other.value;  
}
```

```
Cell<String> s;  
Cell<Object> o;  
s = new Cell<String>();  
o = new Cell<Object>();  
o.copyFrom( s );
```

Wildcards vs. Method Type Parameters

```
void copyFrom( Cell<? extends T> other ) {  
    value = other.value;  
}
```

```
<S extends T> void copyFrom( Cell<S> other ) {  
    value = other.value;  
}
```

```
Cell<String> s;  
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s = new Cell<String>();  
o = new Cell<Object>();  
o.copyFrom( s );
```

Identical client code:
instantiations of
wildcard and method
type argument are
inferred

Wildcards vs. Method Type Parameters

```
void copyFrom( Cell<? extends T> other ) {  
    value = other.value;  
}
```

```
<S extends T> void copyFrom( Cell<S> other ) {  
    value = other.value;  
}
```

```
void copyTo( Cell<? super T> other ) {  
    other.value = value;  
}
```

```
<S super T> void copyTo( Cell<S> other ) {  
    other.value = value;  
}
```

```
Cell<String> s;  
Cell<Object> o;  
s = new Cell<String>();  
o = new Cell<Object>();  
o.copyFrom( s );
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<S super T> void copyTo( Cell<S> other ) {  
    other.value = value;  
}
```

```
Cell<String> s;  
Cell<Object> o;  
s = new Cell<String>();  
o = new Cell<Object>();  
o.copyFrom( s );
```

Identical client code:
instantiations of
wildcard and method
type argument are
inferred

Java does not support
lower bounds for type
parameters

Wildcards vs. Class Type Parameters

```
class Wrapper {  
    Cell<?> data;  
}
```

```
class Wrapper<T> {  
    Cell<T> data;  
}
```

Wildcards vs. Class Type Parameters

```
class Wrapper {  
    Cell<?> data;  
}
```

```
Wrapper w = new Wrapper( );  
w.data = new Cell<String>( );  
w.data = new Cell<Object>( );
```

```
class Wrapper<T> {  
    Cell<T> data;  
}
```

Wildcards vs. Class Type Parameters

```
class Wrapper {  
    Cell<?> data;  
}
```

```
Wrapper w = new Wrapper( );  
w.data = new Cell<String>( );  
w.data = new Cell<Object>( );
```

```
class Wrapper<T> {  
    Cell<T> data;  
}
```

```
Wrapper<Object> w = new Wrapper<Object>( );  
w.data = new Cell<String>( );  
w.data = new Cell<Object>( );
```

Wildcards vs. Class Type Parameters

```
class Wrapper {  
  Cell<?> data;  
}
```

Instantiation can
change over time

```
Wrapper w = new Wrapper( );  
w.data = new Cell<String>( );  
w.data = new Cell<Object>( );
```

```
class Wrapper<T> {  
  Cell<T> data;  
}
```

```
Wrapper<Object> w = new Wrapper<Object>( );  
w.data = new Cell<String>( );  
w.data = new Cell<Object>( );
```

Wildcards vs. Class Type Parameters

```
class Wrapper {  
  Cell<?> data;  
}
```

Instantiation can
change over time

```
Wrapper w = new Wrapper( );  
w.data = new Cell<String>( );  
w.data = new Cell<Object>( );
```

```
class Wrapper<T> {  
  Cell<T> data;  
}
```

```
Wrapper<Object> w = new Wrapper<Object>( );  
w.data = new Cell<String>( );  
w.data = new Cell<Object>( );
```

With type argument,
instantiation is fixed
when object is created

Subtyping and Generics: Wildcards

- The bounds for a wildcard determine the set of possible instantiations

```
Cell<? extends Person> c;  
Cell<? super PhDStudent> d;
```

- For types S and T with the same class or interface, S is a subtype of T if for each type argument, the set of possible instantiations for S is a subset of the set of possible instantiations for T

Subtyping and Generics: Wildcards

- The bounds for a wildcard determine the set of possible instantiations

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- For types S and T with the same class or interface, S is a subtype of T if for each type argument, the set of possible instantiations for S is a subset of the set of possible instantiations for T

```
c = new Cell<Student>( );
```

Subtyping and Generics: Wildcards

- The bounds for a wildcard determine the set of possible instantiations

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- For types S and T with the same class or interface, S is a subtype of T if for each type argument, the set of possible instantiations for S is a subset of the set of possible instantiations for T

```
c = new Cell<Student>( );
```

Instantiation is fixed
(singleton set)

Subtyping and Generics: Wildcards

- The bounds for a wildcard determine the set of possible instantiations

```
Cell<? extends Person> c;  
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```

- For types S and T with the same class or interface, S is a subtype of T if for each type argument, the set of possible instantiations for S is a subset of the set of possible instantiations for T

```
c = new Cell<Student>( );
```

Instantiation is fixed
(singleton set)

```
Cell<? extends Student> e = ...;  
c = e;
```

Decidability

- Whether S is a subtype of T is undecidable in Java due to wildcards

```
class T { }  
  
class N<Z> { }  
  
class C<X> extends N<N<? super C<C<X>>>> {  
    public N<? super C<T>> foo( C<T> c ) {  
        return c;  
    }  
}
```

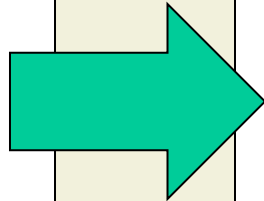
- In fact, Java generics are Turing-complete

Type Erasure

- Java introduced generics in version 5
- For **backwards compatibility**, Sun did not want to change the virtual machine
- **Generic type information is erased** by compiler
 - $C<T>$ is translated to C
 - T is translated to its upper bound
 - Casts are added where necessary
- Only one classfile and only one class object to represent all instantiations of a generic class

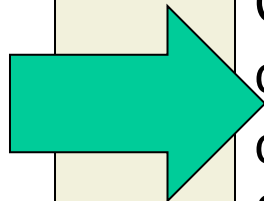
Type Erasure: Example

```
class Cell<T extends Object> {  
    T value;  
  
    void set( T v ) {  
        value = v;  
    }  
  
    T get( ) {  
        return value;  
    }  
}
```



```
class Cell {  
    Object value;  
  
    void set( Object v ) {  
        value = v;  
    }  
  
    Object get( ) {  
        return value;  
    }  
}
```

```
Cell<String> c;  
c = new Cell<String>( );  
c.set( "Hello" );  
String s = c.get( );
```



```
Cell c;  
c = new Cell( );  
c.set( "Hello" );  
String s = ( String ) c.get( );
```

Erasure: Missing Run-Time Information

```
void foo( Object c ) {  
    if( c instanceof Cell<String> )  
        ...  
}
```

Java

Erasure: Missing Run-Time Information

```
void foo( Object c ) {  
    if( c instanceof Cell<String> )  
        ...  
}
```

Java

Compile-time error:
generic types not
allowed with **instanceof**

Erasure: Missing Run-Time Information

```
void foo( Object c ) {  
    if( c instanceof Cell<String> )  
        ...  
}
```

Java

Compile-time error:
generic types not
allowed with **instanceof**

```
Class c = Cell<String>.class;
```

Java

Erasure: Missing Run-Time Information

```
void foo( Object c ) {  
    if( c instanceof Cell<String> )  
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Compile-time error:
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Class c = Cell<String>.class;
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Java

Compile-time error:
class object of generic
types not available

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void foo( Object c ) {  
    if( c instanceof Cell<String> )  
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Class c = Cell<String>.class;
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Java

Compile-time error:
class object of generic
types not available

```
Cell<String>[ ] a;  
a = new Cell<String>[10];
```

Java

Erasure: Missing Run-Time Information

```
void foo( Object c ) {  
    if( c instanceof Cell<String> )  
        ...  
}
```

Java

Compile-time error:
generic types not
allowed with **instanceof**

```
Class c = Cell<String>.class;
```

Java

Compile-time error:
class object of generic
types not available

```
Cell<String>[ ] a;  
a = new Cell<String>[10];
```

Java

Compile-time error:
arrays of generic types
not allowed

Run-Time Information for Generics in C#

```
void Foo( object c ) {  
    if( c is Cell<string> )  
        ...  
}
```

C#

Run-Time Information for Generics in C#

```
void Foo( object c ) {  
    if( c is Cell<string> )  
        ...  
}
```

C# can perform
dynamic type test

C#

Run-Time Information for Generics in C#

```
void Foo( object c ) {  
    if( c is Cell<string> )  
        ...  
}
```

C# can perform
dynamic type test

C#

```
System.Type type = typeof( Cell<string> );
```

C#

Run-Time Information for Generics in C#

```
void Foo( object c ) {  
    if( c is Cell<string> )  
        ...  
}
```

C# can perform
dynamic type test

C#

```
System.Type type = typeof( Cell<string> );
```

C# has run-time
representation

Run-Time Information for Generics in C#

```
void Foo( object c ) {  
    if( c is Cell<string> )  
        ...  
}
```

C# can perform
dynamic type test

C#

```
System.Type type = typeof( Cell<string> );
```

C# has run-time
representation

```
Cell<String>[ ] a;  
a = new Cell<string>[10];
```

C#

Run-Time Information for Generics in C#

```
void Foo( object c ) {  
    if( c is Cell<string> )  
        ...  
}
```

C# can perform
dynamic type test

C#

```
System.Type type = typeof( Cell<string> );
```

C# has run-time
representation

```
Cell<String>[ ] a;  
a = new Cell<string>[10];
```

C# can perform run-time
check for array update

Erasure: Missing Run-Time Checks

```
String demo( Cell<?> c ) {  
    Cell<String> cs = ( Cell<String> ) c;  
    ...  
    return cs.value;  
}
```

Java

Erasure: Missing Run-Time Checks

```
String demo( Cell<?> c ) {  
    Cell<String> cs = ( Cell<String> ) c;  
    ...  
    return cs.value;  
}
```

Java

```
void main( ) {  
    Cell<Object> co = new Cell<Object>( );  
    co.value = new Integer( 5 );  
    demo( co );  
}
```

Java

Erasure: Missing Run-Time Checks

```
String demo( Cell<?> c ) {  
    Cell<String> cs = ( Cell<String> ) c;  
    ...  
    return cs.value;  
}
```

Java

```
String demo( Cell c ) {  
    Cell cs = ( Cell ) c;  
    ...  
    return ( String ) cs.value;  
}
```

Java

```
void main( ) {  
    Cell<Object> co = new Cell<Object>( );  
    co.value = new Integer( 5 );  
    demo( co );  
}
```

Java

```
void main( ) {  
    Cell co = new Cell( );  
    co.value = new Integer( 5 );  
    demo( co );  
}
```

Java

Erasure: Missing Run-Time Checks

```
String demo( Cell<?> c ) {  
    Cell<String> cs = ( Cell<String> ) c;  
    ...  
    return cs.value;  
}
```

No run-time
check for
generic type

```
String demo( Cell c ) {  
    Cell cs = ( Cell ) c;  
    ...  
    return ( String ) cs.value;  
}
```

Java

```
void main( ) {  
    Cell<Object> co = new Cell<Object>( );  
    co.value = new Integer( 5 );  
    demo( co );  
}
```

Java

```
void main( ) {  
    Cell co = new Cell( );  
    co.value = new Integer( 5 );  
    demo( co );  
}
```

Java

Erasure: Missing Run-Time Checks

```
String demo( Cell<?> c ) {  
    Cell<String> cs = ( Cell<String> ) c;  
    ...  
    return cs.value;  
}
```

Run-time error:
cs.value is not
a string

No run-time
check for
generic type

```
void main( ) {  
    Cell<Object> co = new Cell<Object>( );  
    co.value = new Integer( 5 );  
    demo( co );  
}
```

Java

```
String demo( Cell c ) {  
    Cell cs = ( Cell ) c;  
    ...  
    return ( String ) cs.value;  
}
```

Java

```
void main( ) {  
    Cell co = new Cell( );  
    co.value = new Integer( 5 );  
    demo( co );  
}
```

Java

Erasure: Missing Run-Time Checks

```
String demo( Cell<?> c ) {
    Cell<String> cs = ( Cell<String> ) c;
    ...
    return cs.value;
}
```

Run-time error:
cs.value is not
a string

No run-time
check for
generic type

```
void main( ) {
    Cell<Object> co = new Cell<Object>( );
    co.value = new Integer( 5 );
    demo( co );
}
```

Weak type invariant:
object in cs is not of
type Cell<String>!

```
String demo( Cell c ) {
    Cell cs = ( Cell ) c;
    ...
    return ( String ) cs.value;
}
```

Java

```
void main( ) {
    Cell co = new Cell( );
    co.value = new Integer( 5 );
    demo( co );
}
```

Java

Erasure: Overloading

- Erasure may affect method signatures

```
class Erasure<S, T> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

Java

Erasure: Overloading

- Erasure may affect method signatures

```
class Erasure<S, T> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

Java

Compile-time error:
name clash: foo(T)
and foo(S) have the
same erasure

Erasure: Overloading

- Erasure may affect method signatures

```
class Erasure<S, T> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

Java

```
class Erasure<S, T> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

C#

Erasure: Overloading

- Erasure may affect method signatures

```
class Erasure<S, T> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

Java

```
class Erasure<S, T> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

C#

Erasure: Overloading

- Erasure may affect method signatures

```
class Erasure<S, T> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

Java

```
class Erasure<S, T> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

C#

```
class Erasure<S, T extends Person> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

Java

Erasure: Overloading

- Erasure may affect method signatures

```
class Erasure<S, T> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

Java

```
class Erasure<S, T> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

C#

```
class Erasure<S, T extends Person> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

Java

Erasure: Overloading

- Erasure may affect method signatures

```
class Erasure<S, T> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

Java

```
class Erasure<S, T> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

C#

```
class Erasure<S, T extends Person> {  
  void foo( S p ) { }  
  void foo( T p ) { }  
}
```

Java

- Erasure in Java is a “leaky abstraction”

Erasure: Static Fields

- In Java, static fields are shared by all instantiations of a generic class

```
class Count<T> {  
    static int c = 0;  
}
```

Erasure: Static Fields

- In Java, static fields are shared by all instantiations of a generic class

```
class Count<T> {  
    static int c = 0;  
}
```

```
Count.c = 1;  
Count.c = 2;
```

Java

Erasure: Static Fields

- In Java, static fields are shared by all instantiations of a generic class

```
class Count<T> {  
  static int c = 0;  
}
```

```
Count.c = 1;  
Count.c = 2;
```

Java

```
Count<string>.c = 1;  
Count<object>.c = 2;
```

C#

C++ Templates

- Templates allow classes and methods to be **parameterized**
- Clients provide instantiations for template parameters

```
template<class T> class Queue {  
    T elem;  
    Queue<T>* next;  
public:  
    void enqueue( T e ) { ... };  
    T dequeue( ) { ... };  
};
```

C++

```
Queue<int> *q;  
q = new Queue<int>( );  
int s = 5;  
q->enqueue( s );  
int t = q->dequeue( );
```

C++

```
template<class T> void fill( T a[ ], T v )  
{ ... };
```

C++

Template Instantiation

```
template<class T> class Queue {  
    T elem;  
    Queue<T>* next;  
    ...  
};
```

```
Queue<int> *q;  
...
```

Template Instantiation

```
class Queueint {  
    int elem;  
    Queueint* next;  
    ...  
};
```

```
Queueint *q;  
...
```

Template Instantiation

```
template<class T> class Queue {  
    T elem;  
    Queue<T>* next;  
    ...  
};
```

Compiler generates
class for given
template instantiation

```
class Queueint {  
    int elem;  
    Queueint* next;  
    ...  
};
```

```
Queue<int> *q;  
...
```

Template Instantiation

```
Queueint *q;  
...
```

Template Instantiation

```
template<class T> class Queue {  
    T elem;  
    Queue<T>* next;  
    ...  
};
```

Compiler generates
class for given
template instantiation

```
class Queueint {  
    int elem;  
    Queueint* next;  
    ...  
};
```

```
Queue<int> *q;  
...
```

Template Instantiation

```
Queueint *q;  
...
```

Client code uses
generated class

Template Instantiation

```
template<class T> class Queue {  
    T elem;  
    Queue<T>* next;  
    ...  
};
```

Compiler generates
class for given
template instantiation

```
class Queueint {  
    int elem;  
    Queueint* next;  
    ...  
};
```

Type checking is
done for generated
class, not for template

```
Queue<int> *q;  
...
```

Template Instantiation

```
Queueint *q;  
...
```

Client code uses
generated class

Templates and Type Checking

```
template<class T> class Queue {  
    T elem; Queue<T>* next;  
public:  
    void enqueue( T e ) {  
        if( next == NULL ) {  
            elem = e; next = new Queue<T>( );  
        } else {  
            if( e.compareTo( elem ) <= 0 )  
            { next->enqueue( elem ); elem = e; }  
            else next->enqueue( e );  
        }  
    };  
    T dequeue( ) { return "Hello"; };  
};
```

Templates and Type Checking

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Compiler does not type
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Templates and Type Checking

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Compiler does not
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Compiler does not type
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Compiles even
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is instantiated

Compiler does not type
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Templates and Type Checking

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Compiler does not
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Queue<int> *q;  
q = new Queue<int>( );
```

Compiles even
though template
is instantiated

```
Queue<int> *q;  
q = new Queue<int>( );  
int s = 5;  
q->enqueue( s );  
int t = q->dequeue( );
```

Compiler does not type
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Templates and Type Checking

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template<class T> class Queue {  
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Compiler does not
check availability
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```
Queue<int> *q;
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```

Compiles even
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is instantiated

Compile-time errors:
template methods
not type correct

```
Queue<int> *q;
q = new Queue<int>( );
int s = 5;
q->enqueue( s );
int t = q->dequeue( );
```

Compiler does not type
check template code

Templates and Type Checking (cont'd)

- Template code is type checked when instantiated
 - Type errors are not detected before instantiation
- No need for upper bounds on type parameters
 - Availability of methods is not checked anyway
 - Template has to document what it expects from its type arguments
- Different instantiations of templates are unrelated
 - Use template methods to write polymorphic methods
- Templates do not require run-time support
 - Run-time types correspond to generated classes

Concepts

```
template<class T> concept Comparable =  
    requires( T a, T b ) {  
        { a.compareTo( b ) } -> std::same_as<bool>;  
    };
```

- Concepts declare syntactic and type constraints

Concepts

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template<class T> concept Comparable =  
    requires( T a, T b ) {  
        { a.compareTo( b ) } -> std::same_as<bool>;  
    };
```

```
template<class T>  
    requires Comparable<T>  
    class Queue {  
        T elem; Queue<T>* next;  
        ...  
    };
```

- Concepts declare syntactic and type constraints
- Can be used to express **structural upper bounds** on template args.

Concepts

```
template<class T> concept Comparable =  
    requires( T a, T b ) {  
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```

```
template<class T>  
    requires Comparable<T>  
    class Queue {  
        T elem; Queue<T>* next;  
        ...  
    };
```

```
Queue<int> *q;  
q = new Queue<int>( );
```

- Concepts declare syntactic and type constraints
- Can be used to express **structural upper bounds** on template args.
- Compiler checks that bounds are satisfied by instantiations

Concepts (cont'd)

```
template<class T> class Queue {  
    T elem; Queue<T>* next;  
public:  
    void enqueue( T e ) {  
        if( next == NULL ) {  
            elem = e; next = new Queue<T>( );  
        } else {  
            if( e.compareTo( elem ) <= 0 )  
            { next->enqueue( elem ); elem = e; }  
            else next->enqueue( e );  
        }  
    };  
};
```

- Use of concepts is not enforced
- Templates without upper bounds still type check (backwards compatibility)
- Modularity issue persists

Template Meta-Programming

```
template<int n> class Fact {  
  public:  
    static const int val = Fact<n-1>::val * n;  
};
```

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Template parameters
need not be types

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Template parameters
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```
template<> class Fact<0> {  
public:  
    static const int val = 1;  
};
```

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Templates can
be specialized

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```
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```

Templates can
be specialized

```
int main( ) {  
    printf( "fact 3 = %d\n", Fact<3>::val );  
    printf( "fact 4 = %d\n", Fact<4>::val );  
    printf( "fact 5 = %d\n", Fact<5>::val );  
    return 0;  
}
```

Template Meta-Programming

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template<int n> class Fact {  
public:  
    static const int val = Fact<n-1>::val * n;  
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Compiler generates
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template<int n> class Fact {  
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```
template<> class Fact<0>  
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Templates can
be specialized

Compiler generates
these instantiations

Through constant
propagation, values
are **computed by
compiler**

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int main( ) {  
    printf( "fact 3 = %d\n", Fact<3>::val );  
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```

Generic Types vs. Templates: Summary

Generic Types

Templates

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- Modular type checking of generic class
 - Overhead (e.g., upper bounds)

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Generic Types vs. Templates: Summary

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- Modular type checking of generic class
 - Overhead (e.g., upper bounds)

Templates

- Type checking per instantiation
 - Flexibility like with structural typing

Generic Types vs. Templates: Summary

Generic Types

- Modular type checking of generic class
 - Overhead (e.g., upper bounds)
- Run-time support desirable

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Generic Types vs. Templates: Summary

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Generic Types vs. Templates: Summary

Generic Types

- Modular type checking of generic class
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- Run-time support desirable
- Typically no meta-programming

Templates

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Generic Types vs. Templates: Summary

Generic Types

- **Modular type checking** of generic class
 - Overhead (e.g., upper bounds)
- **Run-time support** desirable
- Typically no meta-programming

Templates

- Type checking per instantiation
 - Flexibility like with structural typing
- No need for run-time support
- **Meta-programming** is Turing-complete

References

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