Concepts of Object-Oriented Programming

Peter Müller
Chair of Programming Methodology

Autumn Semester 2022

ETH zürich

4. Types

4.1 Bytecode Verification

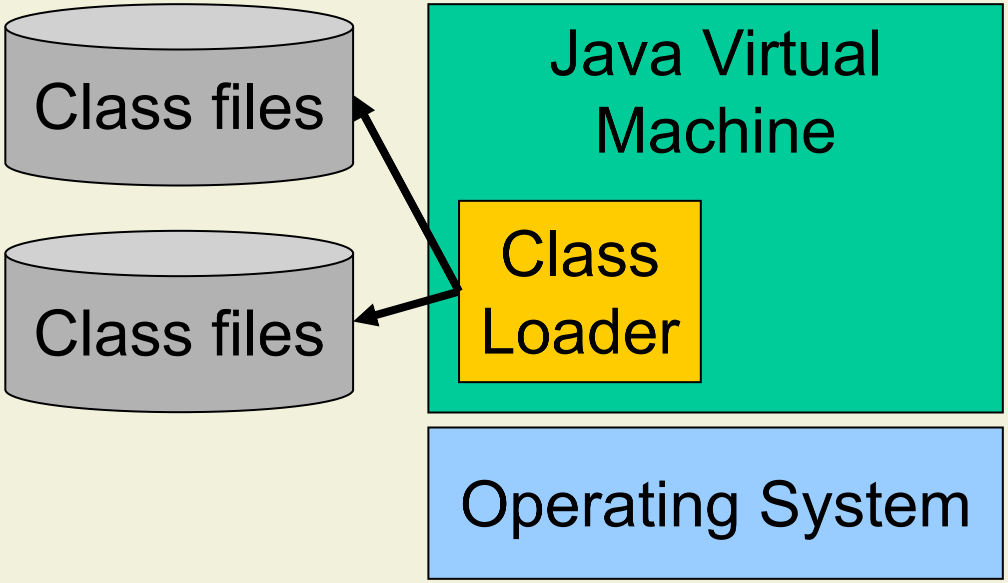
4.2 Parametric Polymorphism

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

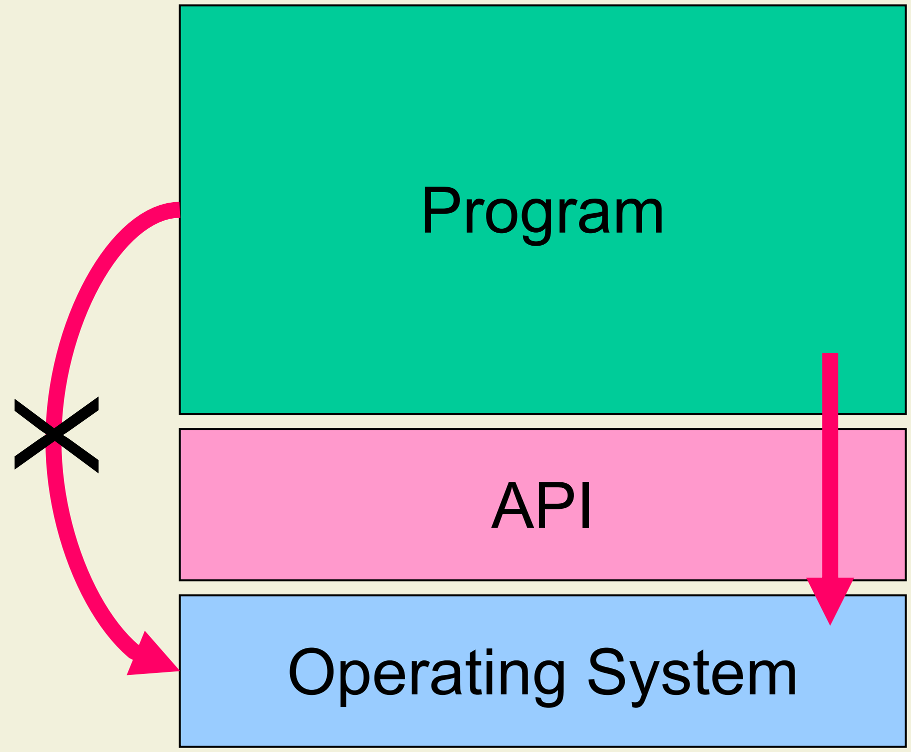
Error handling partly omitted

```
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 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

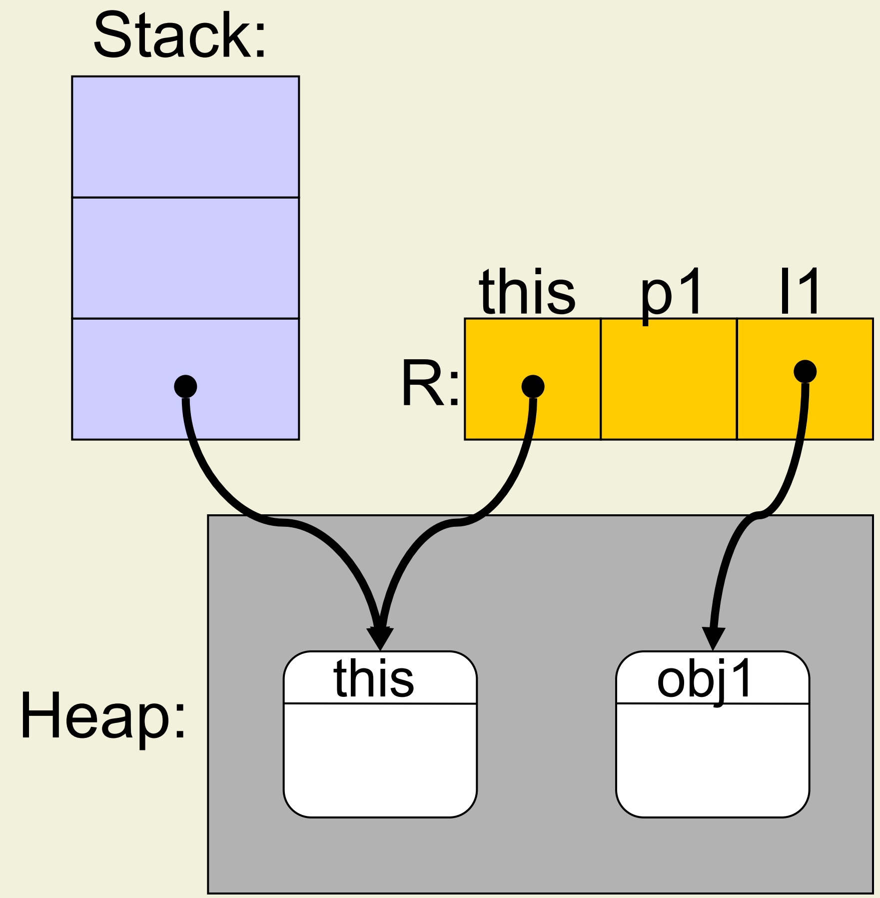


Security in Mobile Environments

- 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

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

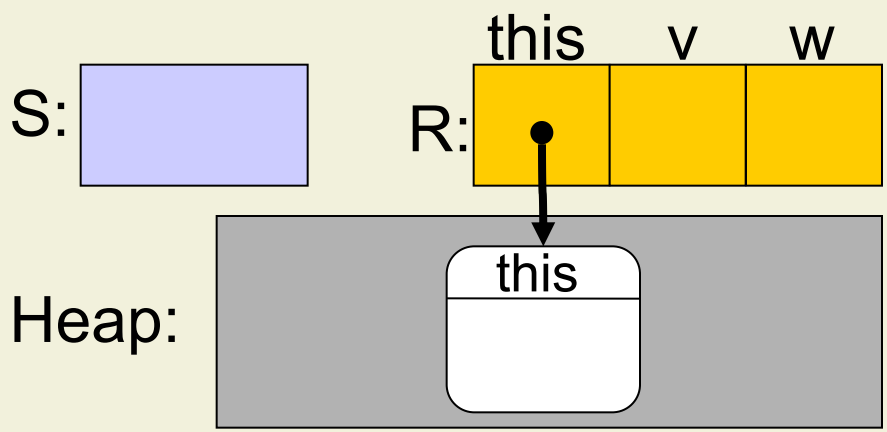


Java Bytecode

- 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
```

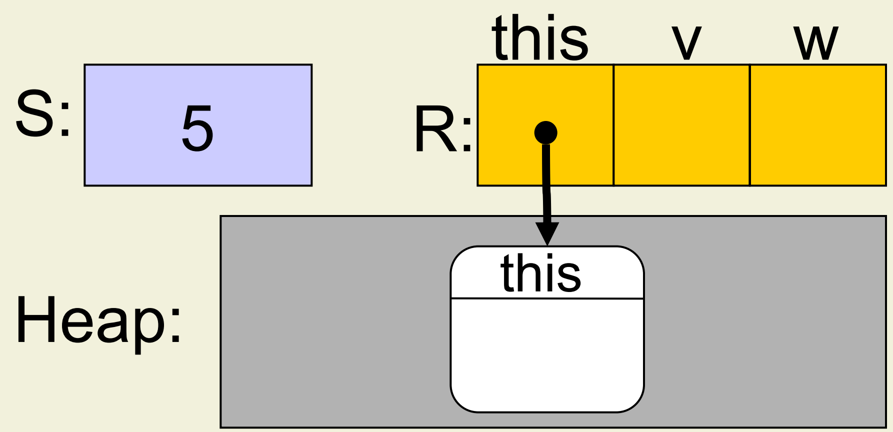


Java Bytecode

- 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
```

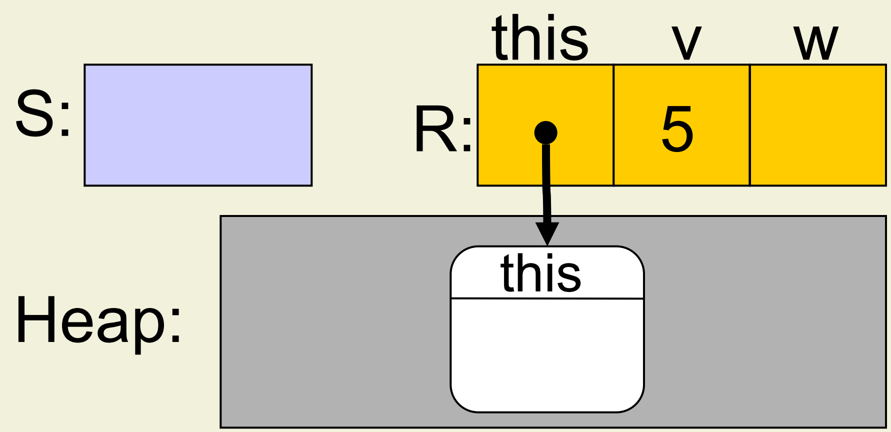


Java Bytecode

- 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
```

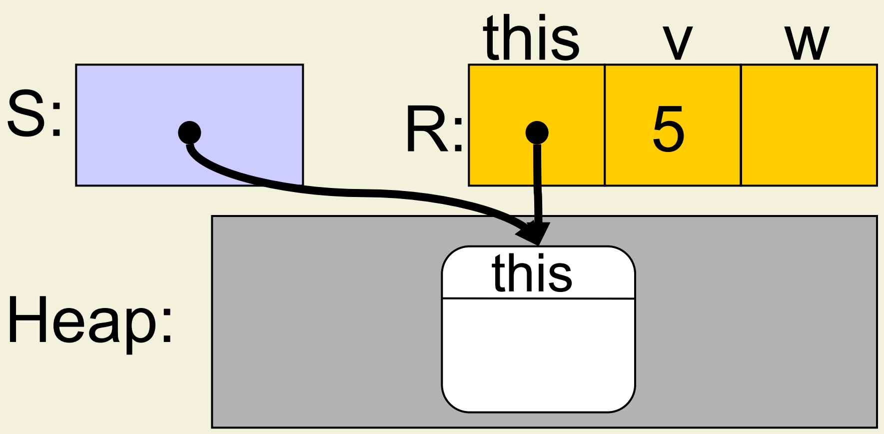


Java Bytecode

- 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
```

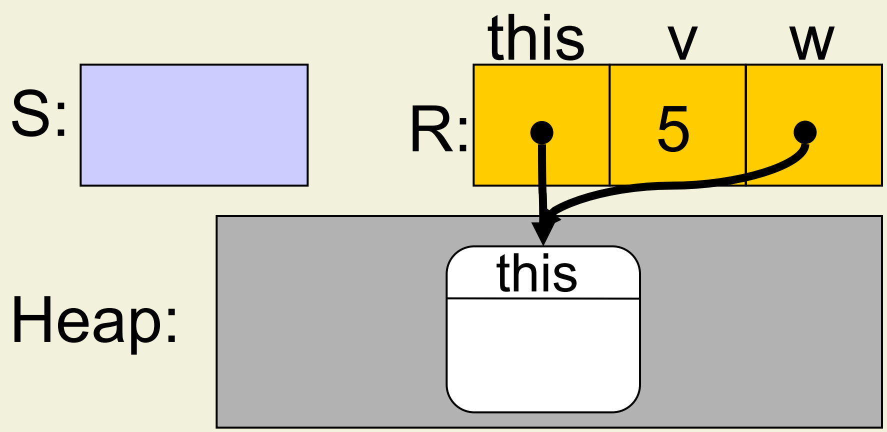


Java Bytecode

- 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
```

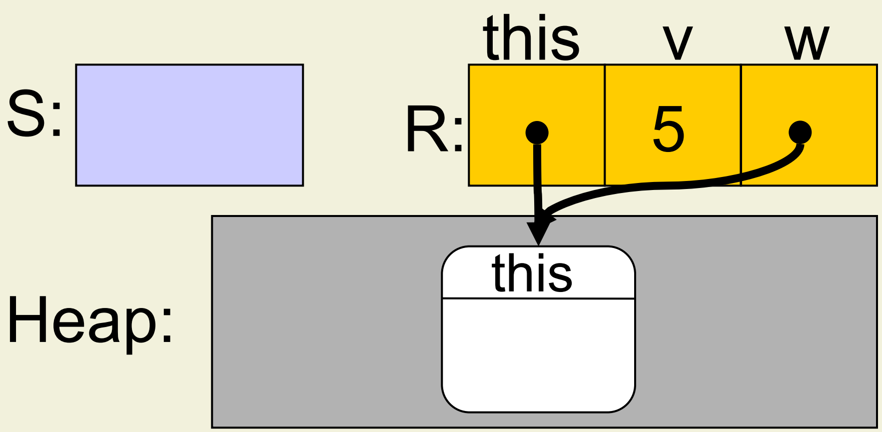


Java Bytecode

- 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
```



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

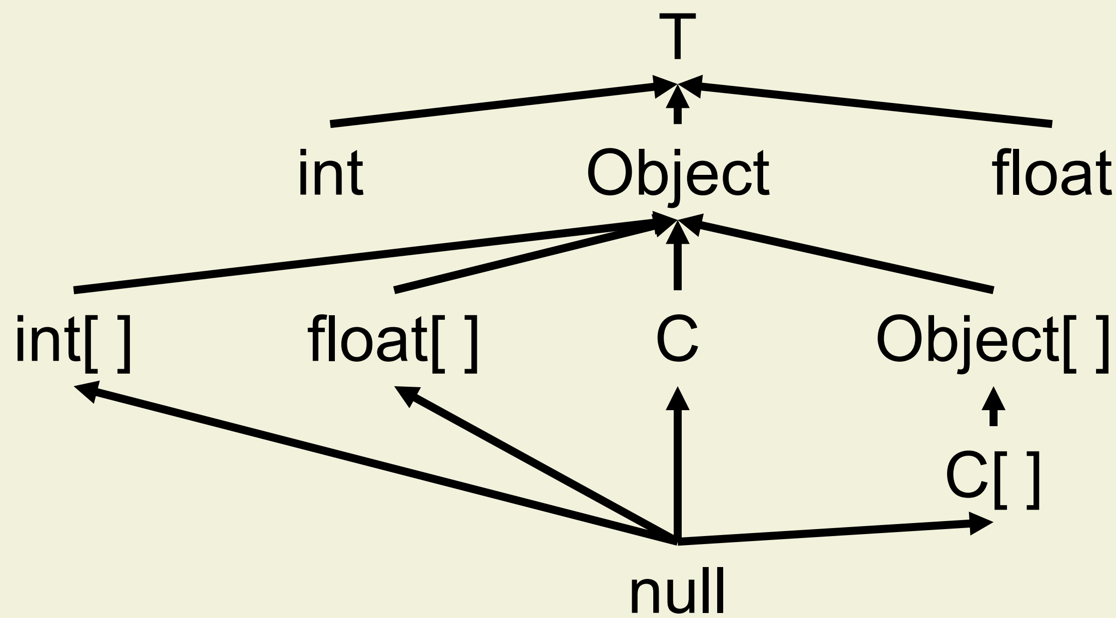
- The Bytecode verifier simulates the execution of the program
- Operations are performed on types instead of values
- For each instruction, a rule describes how the operand stack and local variables are modified

$$i: (S,R) \rightarrow (S',R')$$
$$iadd: (int.int.S,R) \rightarrow (int.S,R)$$

- 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:

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

iload n:

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

astore n:

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

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

Example

this v w

int v;	iconst 5	([ ] , [C,T,T]) →
Object w;	istore 1	(int , [C,T,T]) →
v = 5;	aload 0	([ ] , [C,int,T]) →
w = **this**;	astore 2	(C , [C,int,T]) →
	return	([ ] , [C,int,C])

int v;	iconst 5	([ ] , [C,T,T]) →
Object w;	istore 1	(int , [C,T,T]) →
v = 5;	iload 1	([ ] , [C,int,T]) →
w = v;	astore 2	(int , [C,int,T])
	return	stuck

astore expects an object type on top of the stack!

Smallest Common Supertype

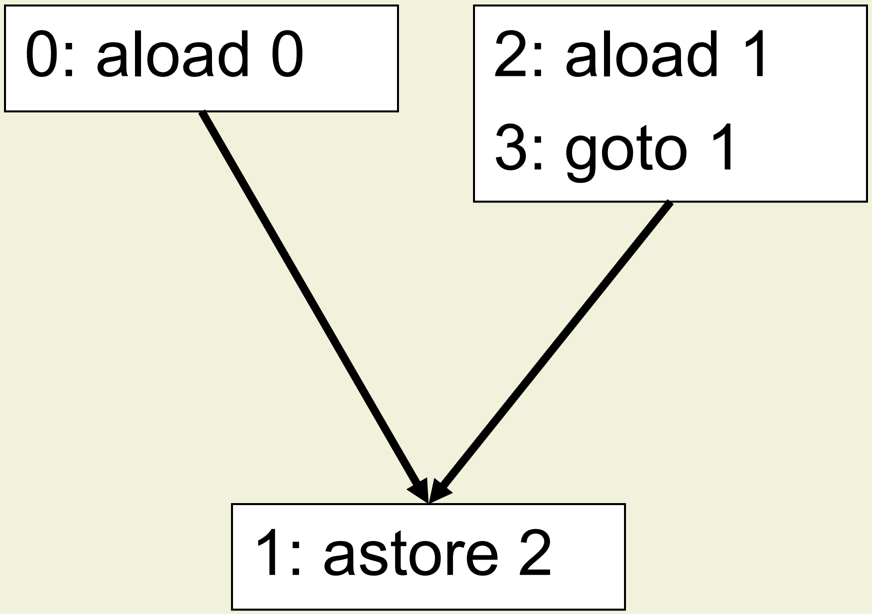
- Jumps may lead to joins in control flow

```
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

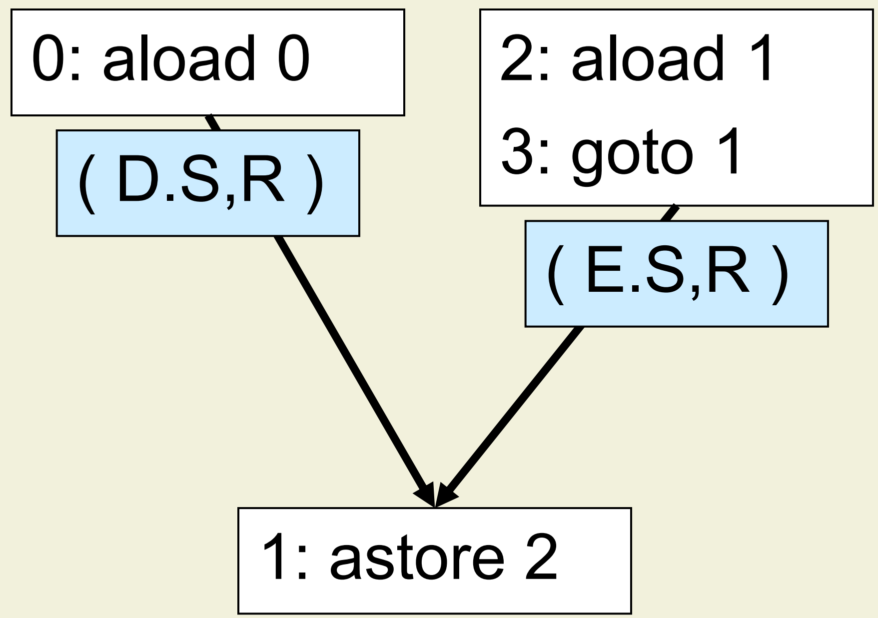
```
0: aload 0
1: astore 2
2: aload 1
3: goto 1
```



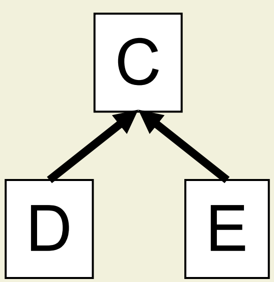
Smallest Common Supertype

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

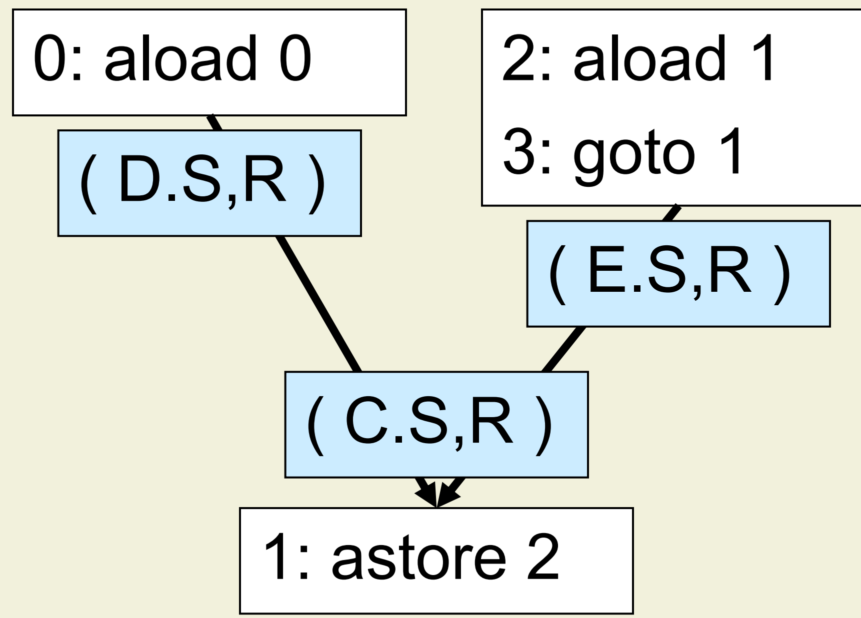
```
0: aload 0
1: astore 2
2: aload 1
3: goto 1
```



Smallest Common Supertype

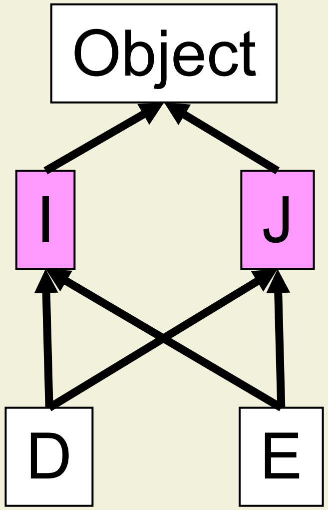
- Jumps may lead to joins in control flow
- Instructions can have several predecessors
- Smallest common supertype is selected (T if no other common supertype exists)
- 


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



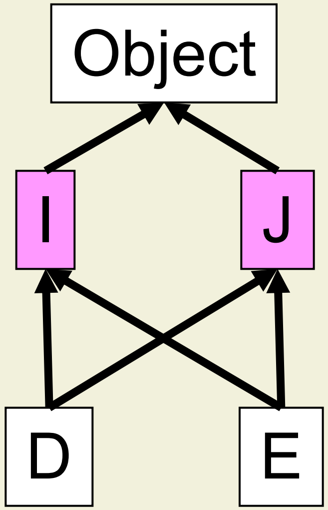
Handling Multiple Subtyping

- With multiple subtyping, several smallest common supertypes may exist
- JVM solution
  - Ignore interfaces
  - Treat all interface types as Object
  - Works because of single inheritance of classes



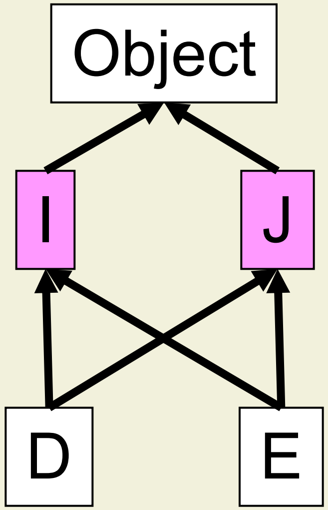
Handling Multiple Subtyping

- With multiple subtyping, several smallest common supertypes may exist
- JVM solution
  - Ignore interfaces
  - Treat all interface types as Object
  - Works because of single inheritance of classes



Handling Multiple Subtyping

- With multiple subtyping, several smallest common supertypes may exist
- 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
  - **R**un-time check is necessary



Inference Algorithm

- Inference is a fixpoint iteration

```
in( 0 ) := ( [ ] , [ P_0,…,P_n,T,…,T ] )
worklist := { i | instr_i is an instruction of the method }
while worklist ≠ ∅ do
  i := min( worklist )
  remove i from worklist
  out( i ) := apply_rule( instr_i, 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

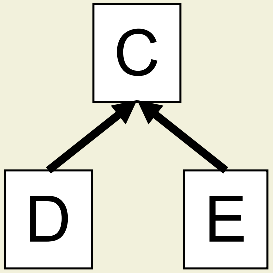
- scs(s,t) is the smallest common supertype of s and t

$$
\begin{aligned}
&\text{pointwise\_scs}(\ ([s_1 \ldots\ldots s_k] , [t_0,\ldots,t_n]) ,\\
&\qquad\qquad ([s'_1 \ldots\ldots s'_k] , [t'_0,\ldots,t'_n])\ ) =\\
&([\text{scs}(s_1,s'_1)\ldots\ldots\text{scs}(s_k,s'_k)] , [\text{scs}(t_0,t'_0),\ldots,\text{scs}(t_n,t'_n)])
\end{aligned}
$$

- 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
```



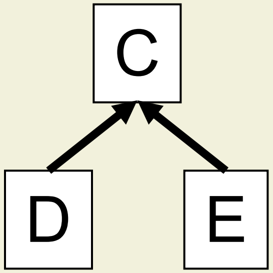
	in	out
0:	([ ] , [D,E,T])	
1:		
2:		
3:		

worklist

0 1 2 3

Inference Example

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



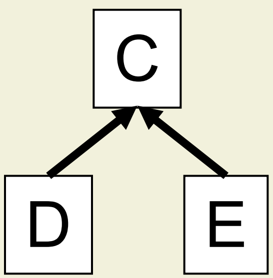
	in	out
0:	([ ] , [D,E,T])	
1:		
2:		
3:		

worklist

1 2 3

Inference Example

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



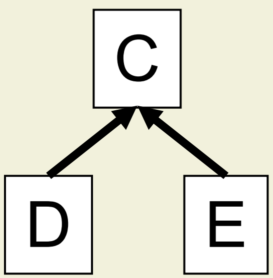
	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:		
2:		
3:		

worklist

1 2 3

Inference Example

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



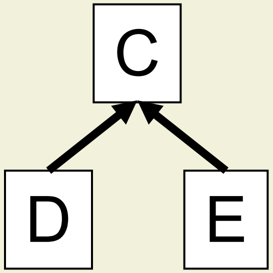
worklist

1 2 3

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

Inference Example

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



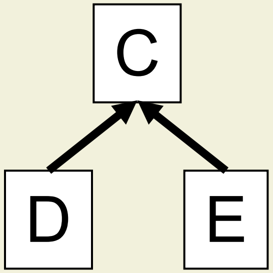
worklist

2 3

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

Inference Example

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



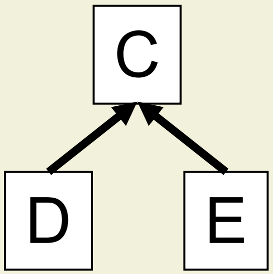
worklist

2 3

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

Inference Example

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



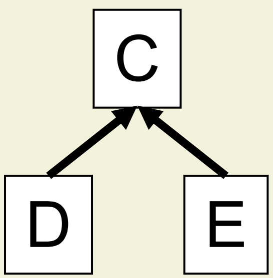
	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T])	([ ] , [D,E,D])
2:	([ ] , [D,E,D])	
3:		

worklist

2 3

Inference Example

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



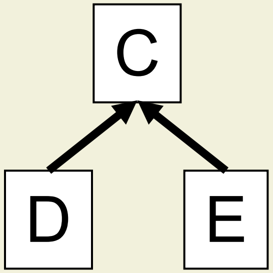
	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T])	([ ] , [D,E,D])
2:	([ ] , [D,E,D])	
3:		

worklist

3

Inference Example

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



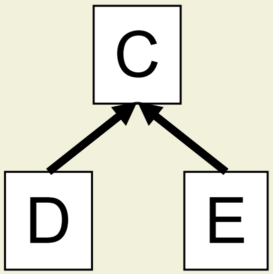
	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T])	([ ] , [D,E,D])
2:	([ ] , [D,E,D])	([E] , [D,E,D])
3:		

worklist

3

Inference Example

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



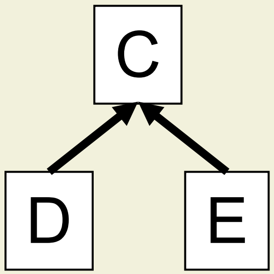
	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T])	([ ] , [D,E,D])
2:	([ ] , [D,E,D])	([E] , [D,E,D])
3:	([E] , [D,E,D])	

worklist

3

Inference Example

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

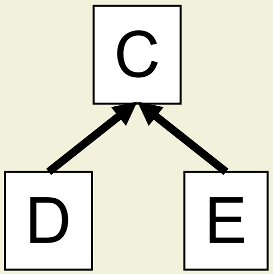


	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T])	([ ] , [D,E,D])
2:	([ ] , [D,E,D])	([E] , [D,E,D])
3:	([E] , [D,E,D])	

worklist

Inference Example

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

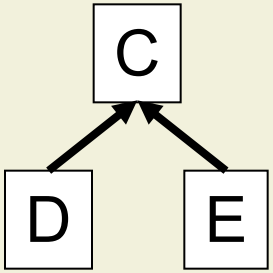


	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T])	([ ] , [D,E,D])
2:	([ ] , [D,E,D])	([E] , [D,E,D])
3:	([E] , [D,E,D])	([E] , [D,E,D])

worklist

Inference Example

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

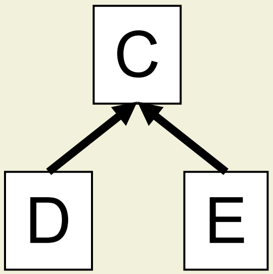


	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D])
2:	([ ] , [D,E,D])	([E] , [D,E,D])
3:	([E] , [D,E,D])	([E] , [D,E,D])

worklist

Inference Example

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

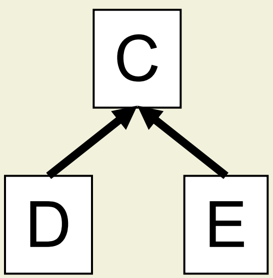


worklist

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



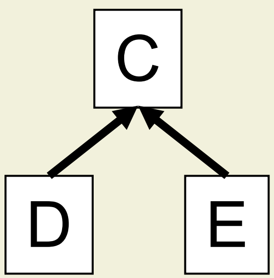
	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D])
2:	([ ] , [D,E,D])	([E] , [D,E,D])
3:	([E] , [D,E,D])	([E] , [D,E,D])

worklist

1

Inference Example

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

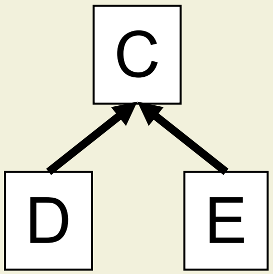


	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D])
2:	([ ] , [D,E,D])	([E] , [D,E,D])
3:	([E] , [D,E,D])	([E] , [D,E,D])

worklist

Inference Example

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

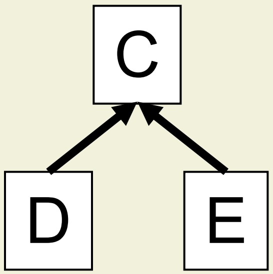


worklist

	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])	([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
```

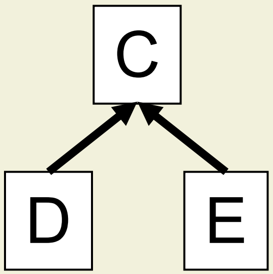


	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D]) ([ ] , [D,E,C])
2:	([ ] , [D,E,D]) ([ ] , [D,E,C])	([E] , [D,E,D])
3:	([E] , [D,E,D])	([E] , [D,E,D])

worklist

Inference Example

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

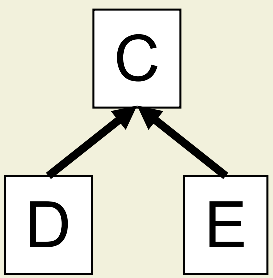


	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D]) ([ ] , [D,E,C])
2:	([ ] , [D,E,D]) ([ ] , [D,E,C])	([E] , [D,E,D])
3:	([E] , [D,E,D])	([E] , [D,E,D])

worklist

Inference Example

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



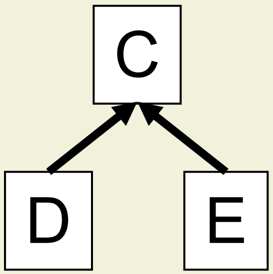
	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D]) ([ ] , [D,E,C])
2:	([ ] , [D,E,D]) ([ ] , [D,E,C])	([E] , [D,E,D])
3:	([E] , [D,E,D])	([E] , [D,E,D])

worklist

2

Inference Example

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

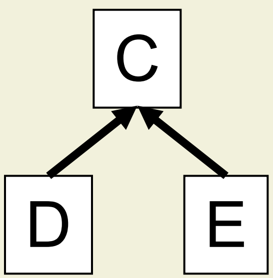


	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D]) ([ ] , [D,E,C])
2:	([ ] , [D,E,D]) ([ ] , [D,E,C])	([E] , [D,E,D])
3:	([E] , [D,E,D])	([E] , [D,E,D])

worklist

Inference Example

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

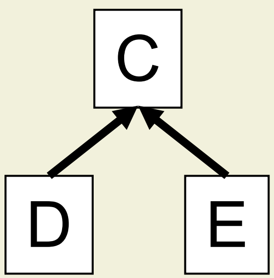


worklist

	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
```



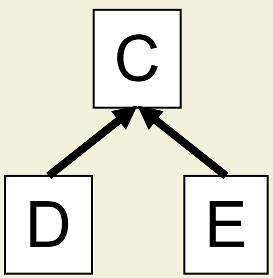
	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D]) ([ ] , [D,E,C])
2:	([ ] , [D,E,D]) ([ ] , [D,E,C])	([E] , [D,E,D]) ([E] , [D,E,C])
3:	([E] , [D,E,D])	([E] , [D,E,D])

worklist

Inference Example

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

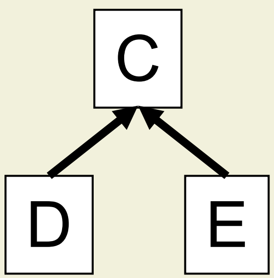
	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D]) ([ ] , [D,E,C])
2:	([ ] , [D,E,D]) ([ ] , [D,E,C])	([E] , [D,E,D]) ([E] , [D,E,C])
3:	([E] , [D,E,D]) ([E] , [D,E,C])	([E] , [D,E,D])



worklist

Inference Example

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



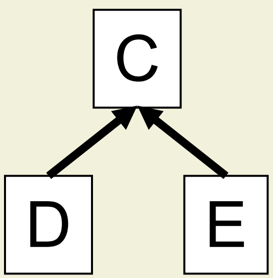
	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D]) ([ ] , [D,E,C])
2:	([ ] , [D,E,D]) ([ ] , [D,E,C])	([E] , [D,E,D]) ([E] , [D,E,C])
3:	([E] , [D,E,D]) ([E] , [D,E,C])	([E] , [D,E,D])

worklist

3

Inference Example

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

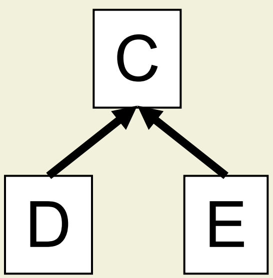


	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D]) ([ ] , [D,E,C])
2:	([ ] , [D,E,D]) ([ ] , [D,E,C])	([E] , [D,E,D]) ([E] , [D,E,C])
3:	([E] , [D,E,D]) ([E] , [D,E,C])	([E] , [D,E,D])

worklist

Inference Example

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

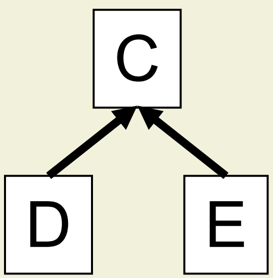


	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D]) ([ ] , [D,E,C])
2:	([ ] , [D,E,D]) ([ ] , [D,E,C])	([E] , [D,E,D]) ([E] , [D,E,C])
3:	([E] , [D,E,D]) ([E] , [D,E,C])	([E] , [D,E,D])

worklist

Inference Example

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



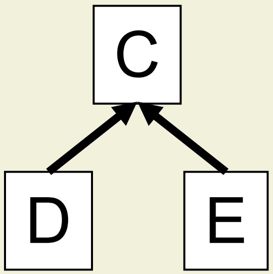
	in	out
0:	([ ] , [D,E,T])	([D] , [D,E,T])
1:	([D] , [D,E,T]) ([C] , [D,E,T])	([ ] , [D,E,D]) ([ ] , [D,E,C])
2:	([ ] , [D,E,D]) ([ ] , [D,E,C])	([E] , [D,E,D]) ([E] , [D,E,C])
3:	([E] , [D,E,D]) ([E] , [D,E,C])	([E] , [D,E,D]) ([E] , [D,E,C])

worklist

Inference Example

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

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



worklist

Type Inference: Discussion

- Advantages
  - Determines the most general solution that satisfies the typing 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

  $\boxed{(\ [\ \text{int}\ ]\ ,\ [\ \text{C,int,T}\ ]\ )}$

- 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 wherever available
- Infer types otherwise

```
foreach basic block of a method body do
  in := types( start )
  foreach { i | instr_i is an instruction of basic block } do
    in := apply_rule( instr_i, 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 Algorithm

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

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

Required types

Type Checking Algorithm

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

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

Required types

Check conditions and infer next configuration

Type Checking Algorithm

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

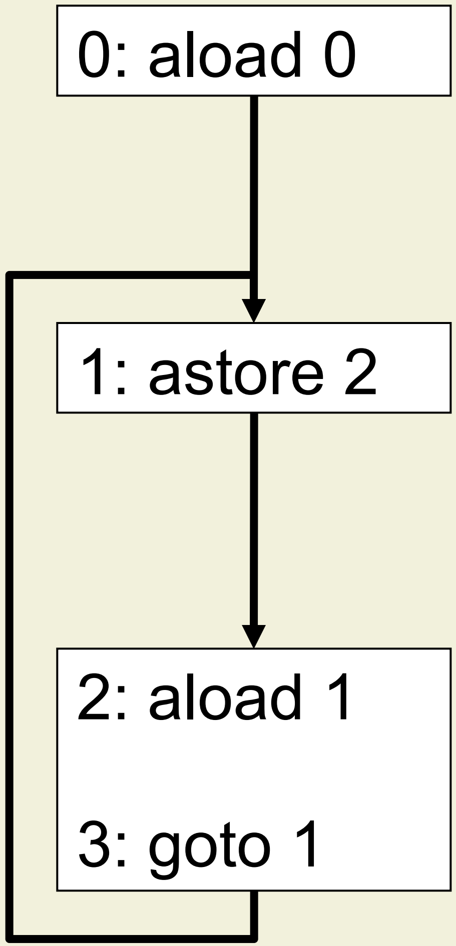
```
foreach basic block of a method body do
  in := types( start )
  foreach { i | instr_i is an instruction of basic block } do
    in := apply_rule( instr_i, in )
    foreach q in successors( i ) do
      if types( q ) is declared then
        check that in is assignable to types( q )
      end
  end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

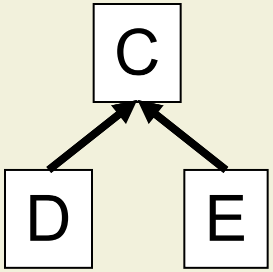
Required types

Check conditions and infer next configuration

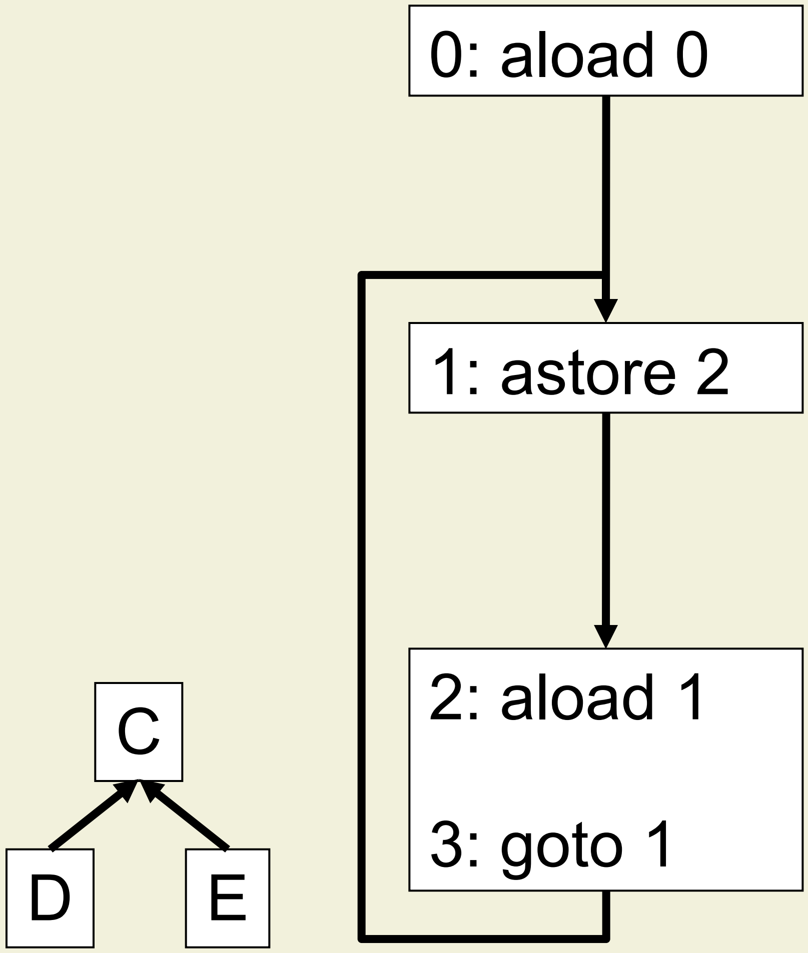
Check declared types

Type Checking Example

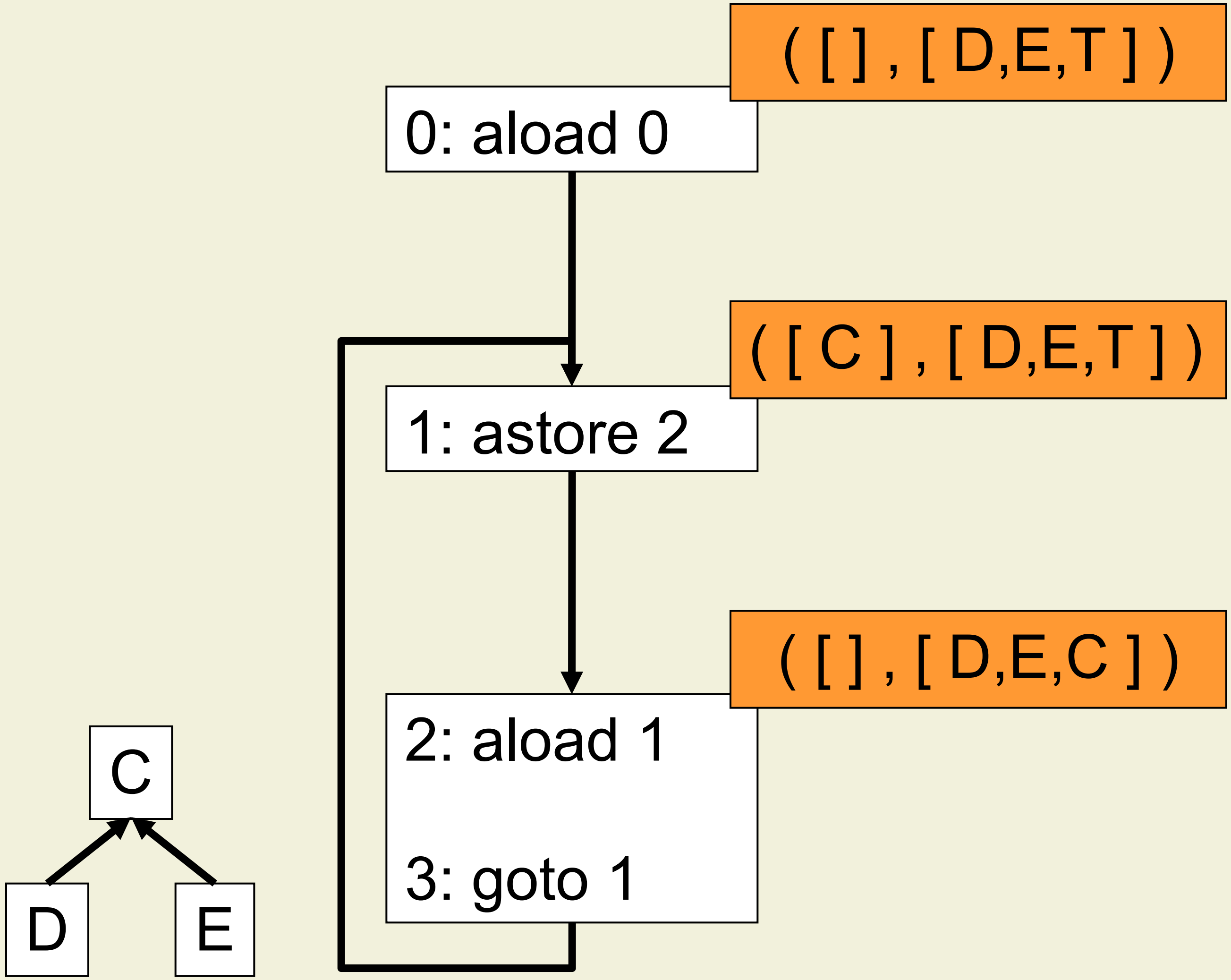




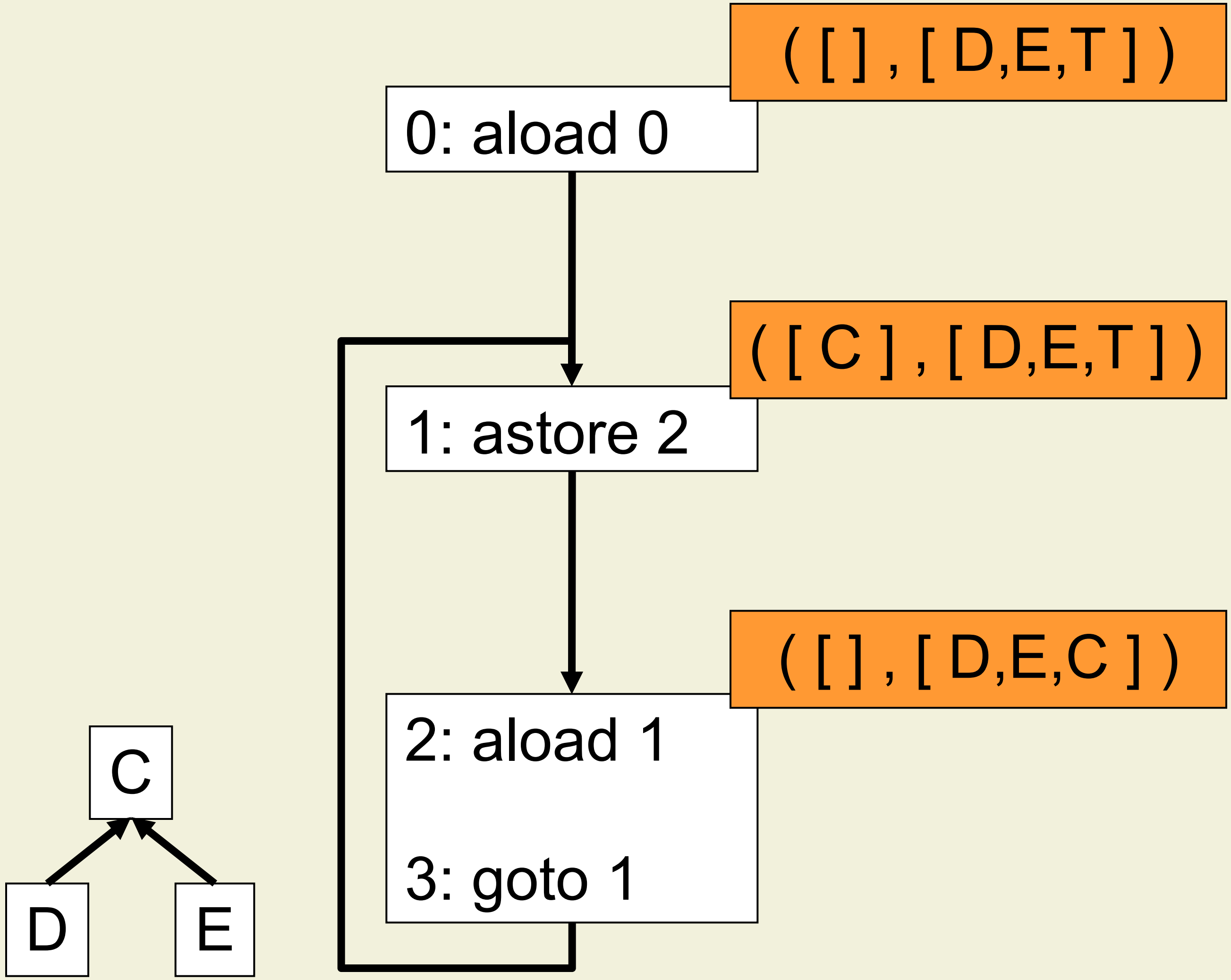
Type Checking Example



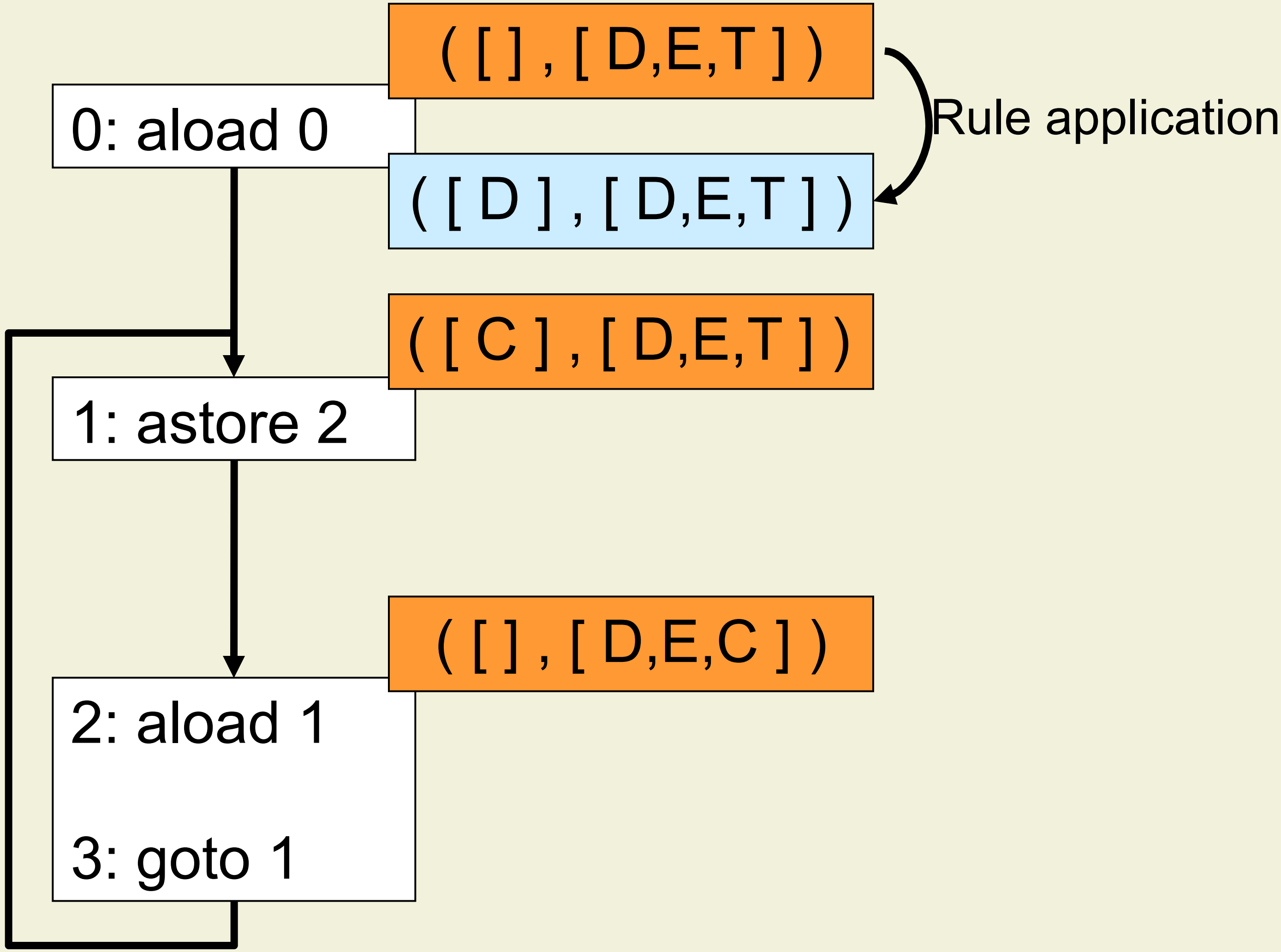
Type Checking Example

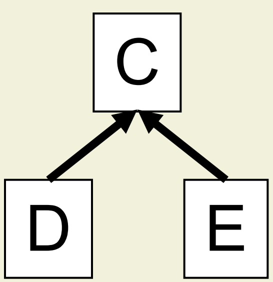


Type Checking Example

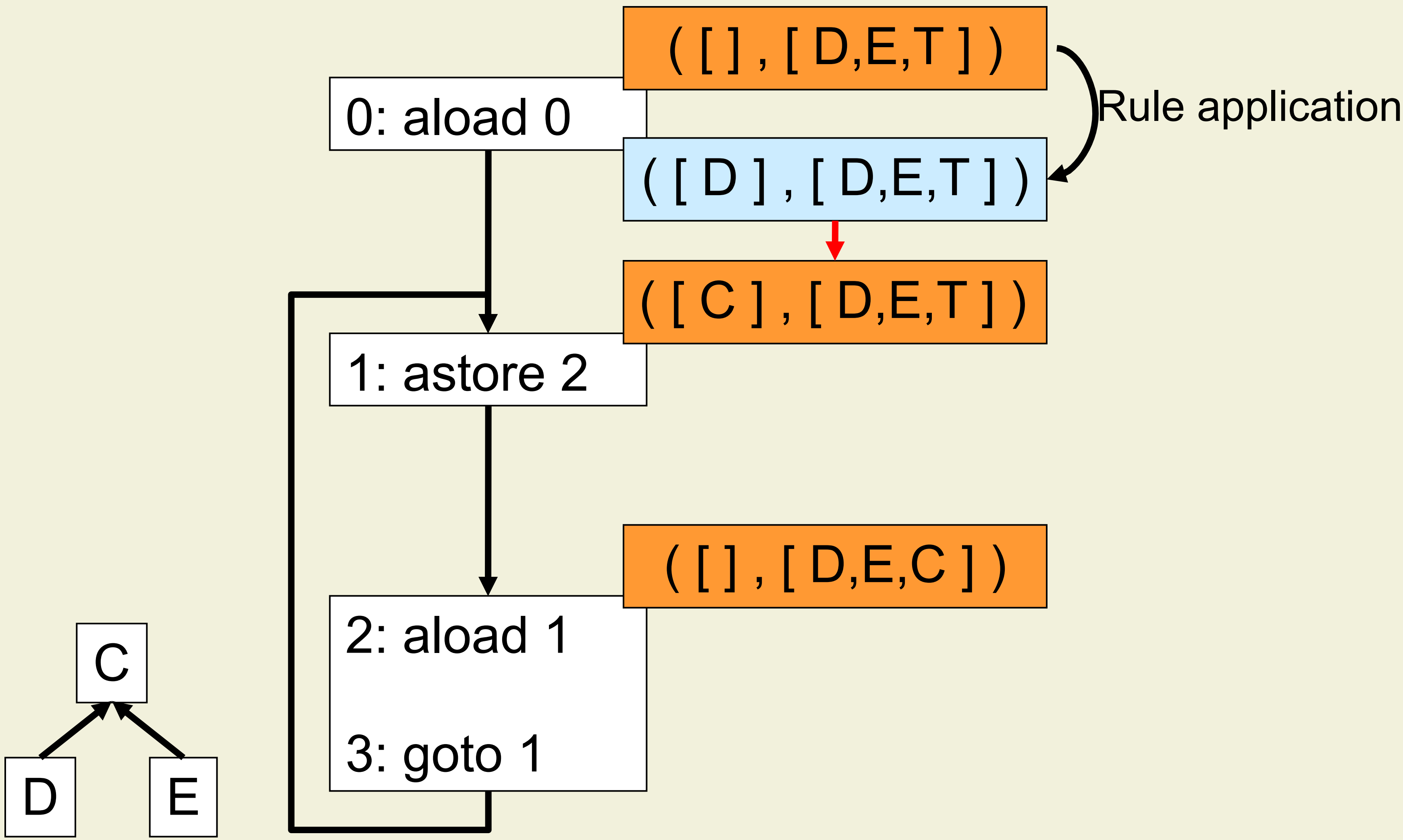


Type Checking Example

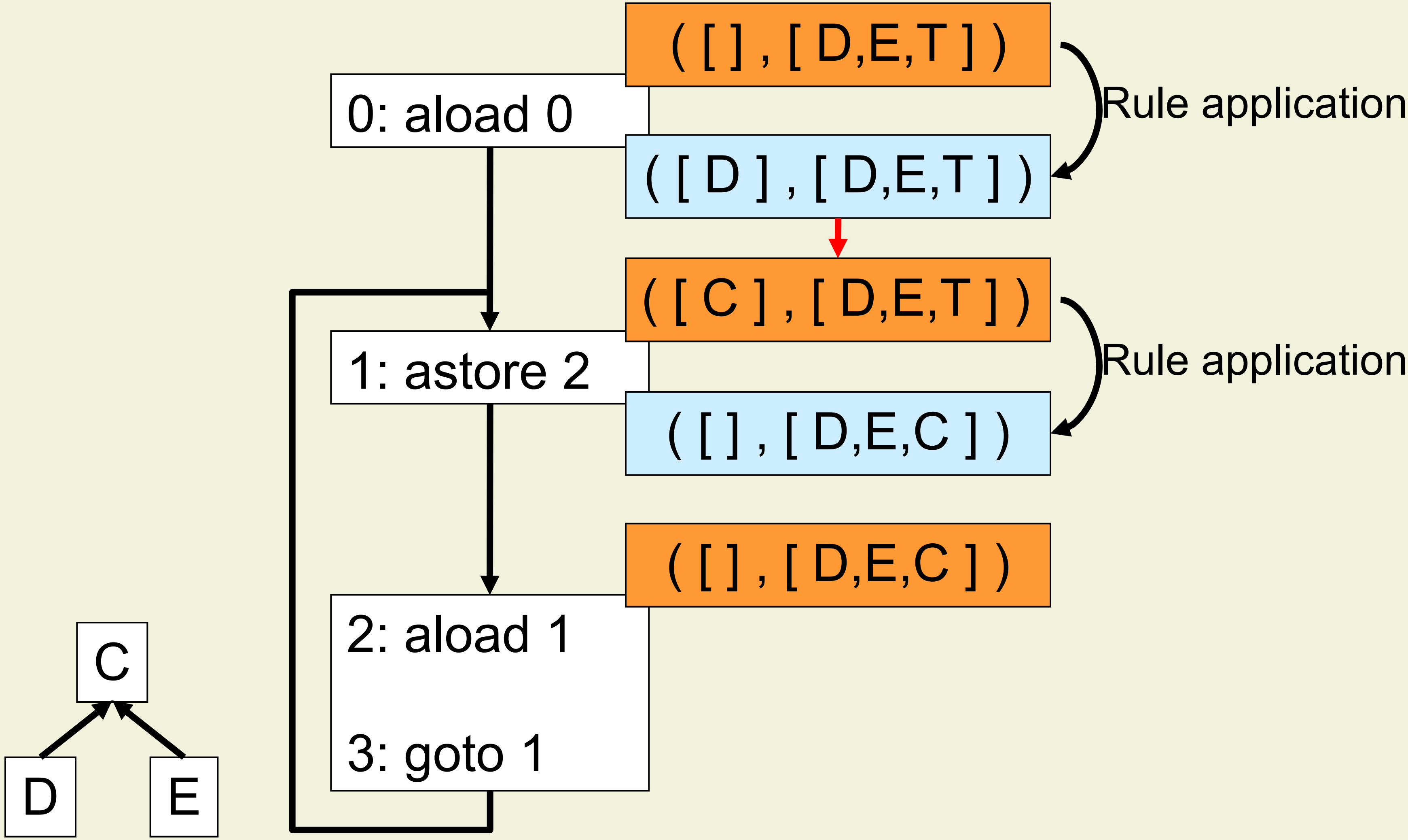




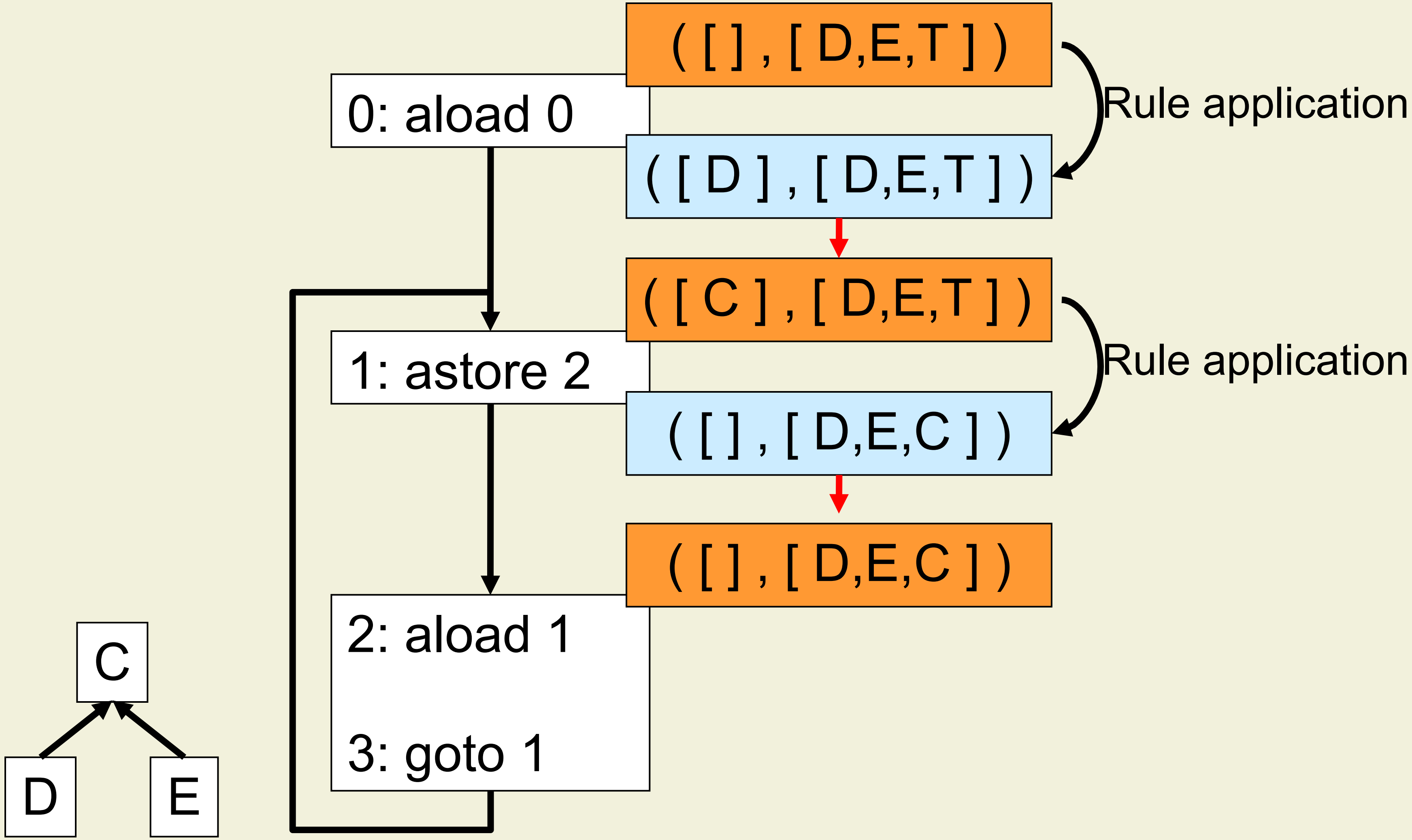
Type Checking Example



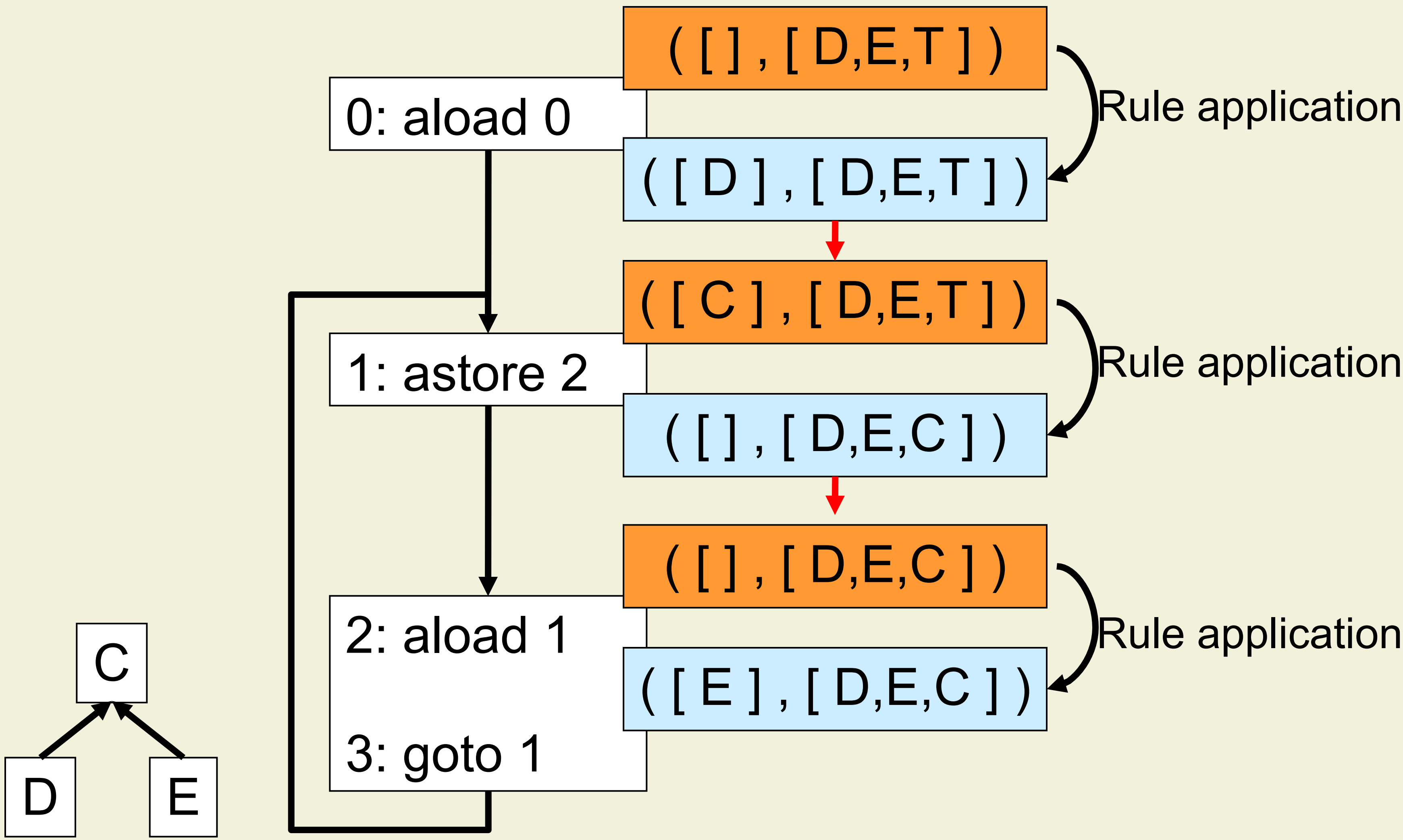
Type Checking Example



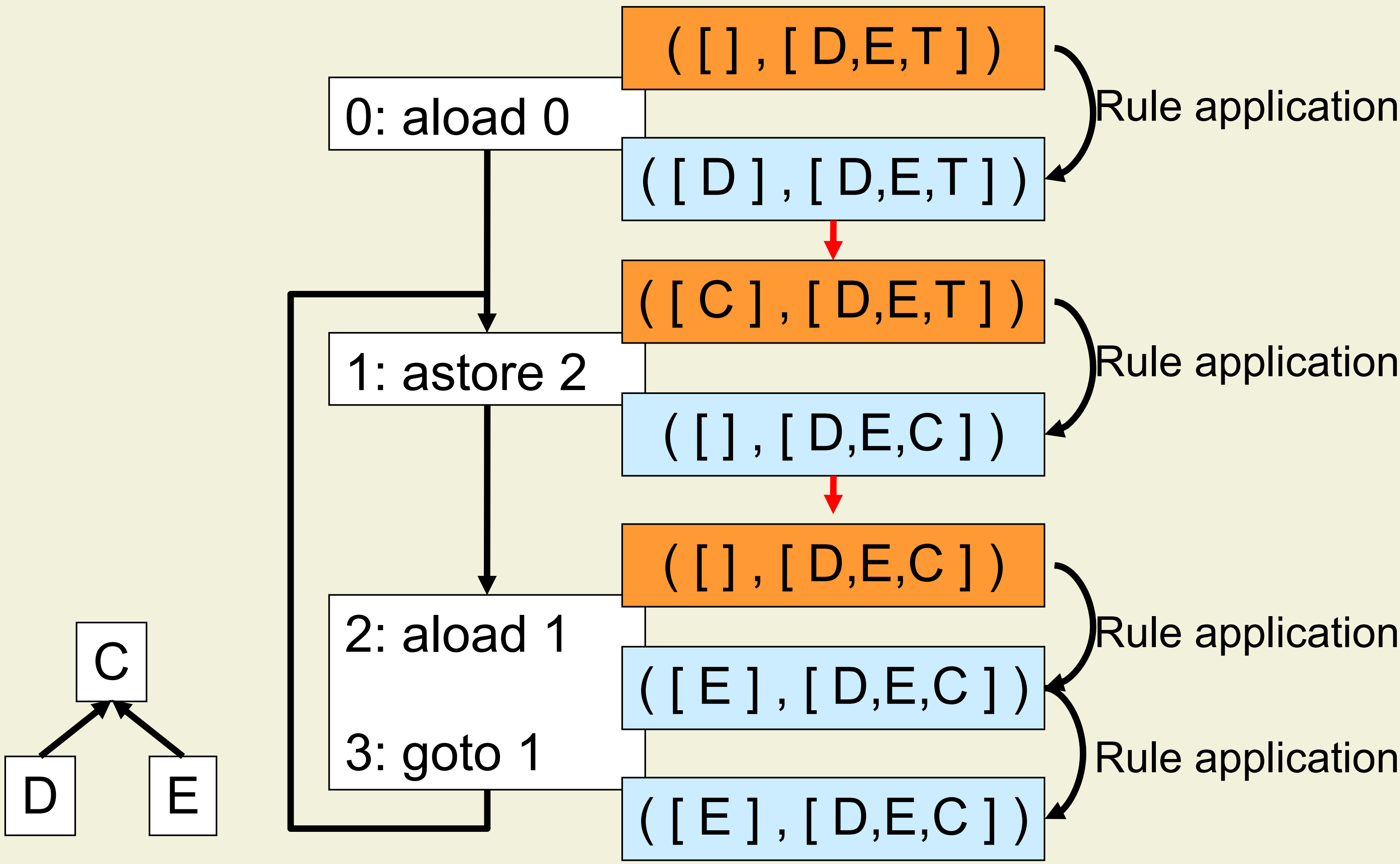
Type Checking Example



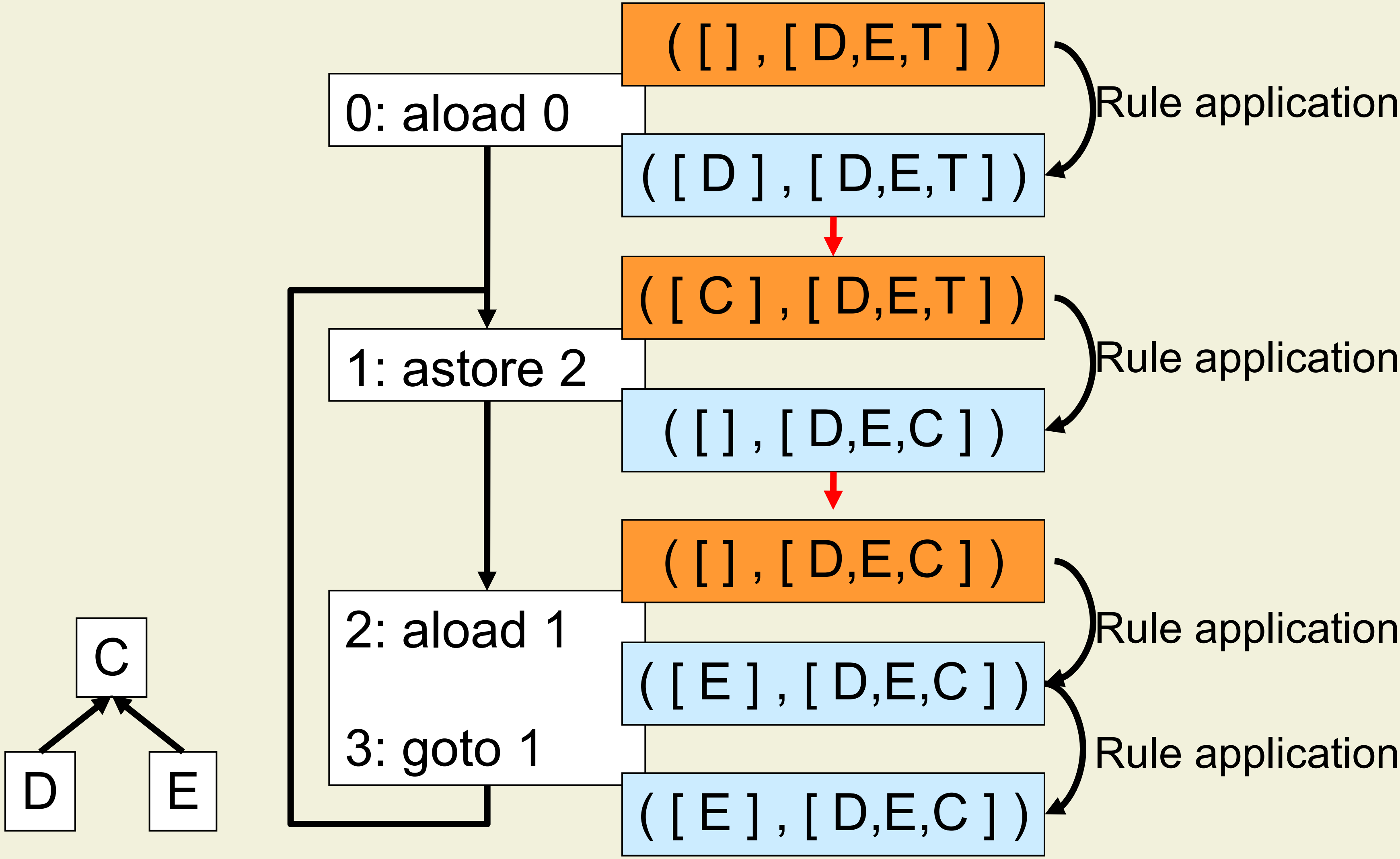
Type Checking Example



Type Checking Example

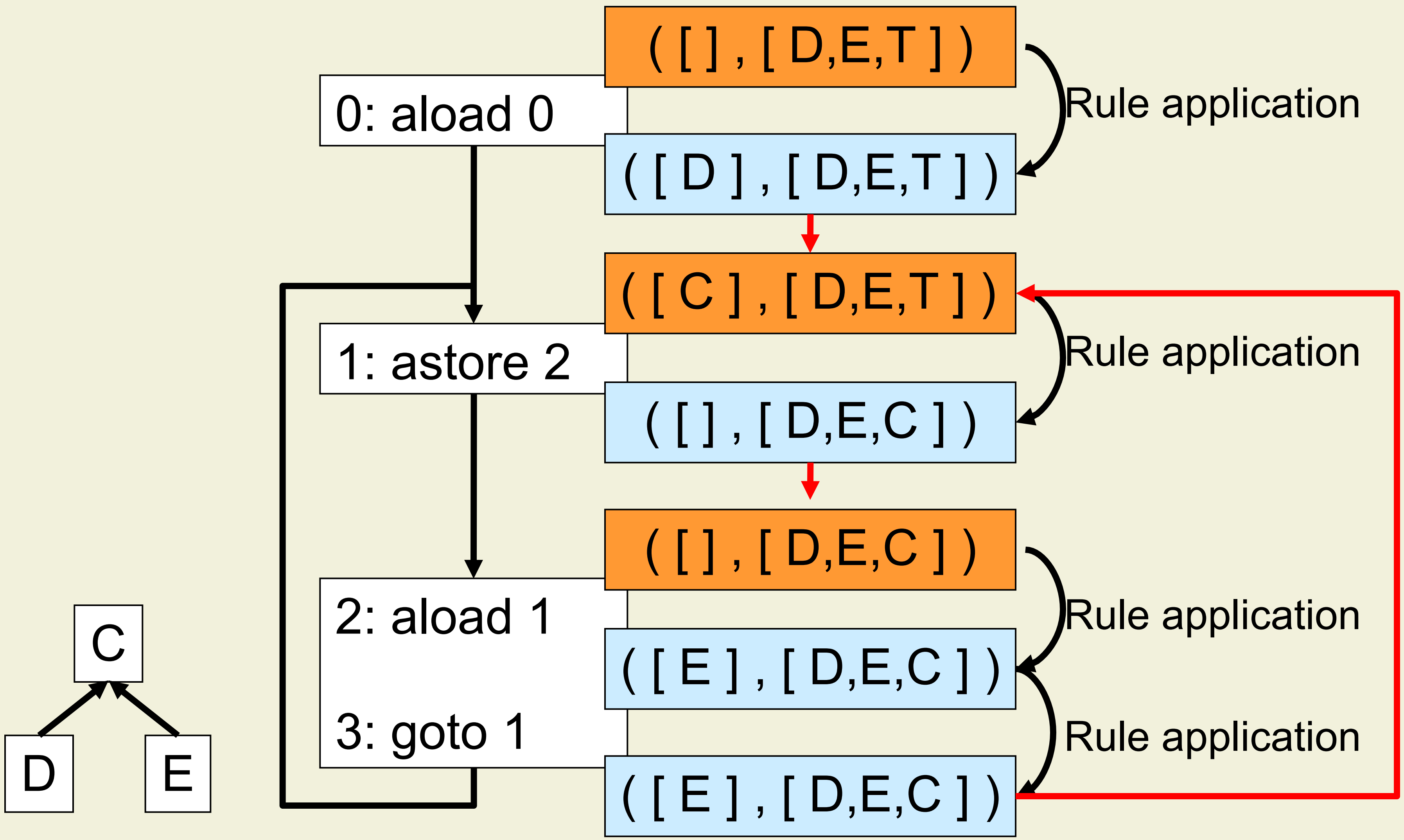


Type Checking Example



ETH zürich

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

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

- Dynamic typing does not require a static type and does not perform static type checking

```
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
  }
}
```

Scala

Inference:
f: Int

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

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

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

```
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

```java
class Queue {
  Object elem;
  Queue next;
  void enqueue( Object e ) { … }
  Object dequeue( ) { … }
}
```
Java

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

```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)

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

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

```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

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

Java

```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

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

Java

```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

Typecheck under the assumption T <: Comparable<T>

Upper Bounds: Example

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

Java

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

Java

```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

Typecheck under the assumption T <: Comparable<T>

Upper Bounds: Example

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

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

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

```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

Typecheck under the
assumption
T <: Comparable<T>

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( ) { … }
}
```

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
  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>

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

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 ) {
  q.enqueue( "Hello" );
}
```

```
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>

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

- Contravariance is unsafe when a generic type argument is used for variables that are read by clients
  - Fields
  - Method results

```
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>

ETH zurich

Java Solution: Non-Variance

- Generic types in Java are non-variant (neither co- 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 co- 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

ETH zürich

Java Solution: Non-Variance

- Generic types in Java are non-variant (neither co- nor contravariant)

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

- Non-variance is statically type safe
  - No run-time checks needed

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

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

- Non-variance is sometimes overly restrictive

```
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>

```
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

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

```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

```scala
class Random[ +T ] {
  def next: T = { … }
}
```
Scala

```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

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

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

- Type checker prevents other occurrences

```
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

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

Scala

```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

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

```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

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

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

```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

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

```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

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

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

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

```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 ) { … }
  … }
```

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

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 ) { … }
}
```

Universal comparator for all persons

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 ) { … }
}
```

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

```
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() );
```

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 ) { … }
}
```

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

```
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 (cont'd)

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

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

Additional Type Parameters (cont'd)

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

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

Additional Type Parameters (cont'd)

```
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 (cont'd)

```
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 (cont'd)

```
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>

Solution 2: Wildcards

- A wildcard represents an unknown type

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

```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

```java
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

```java
Collection<String> c = new ArrayList<String>( );
…
printAll( c );
```
Java

Wildcard instantiated with String

ETH zürich

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

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

Two existential types

Wildcard Examples

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

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

Two existential types

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

ETH zürich

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 );
}
```

```
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 );
}
```

```
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 ? <: 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;
  }
}
```

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

```
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

```
class Cell<T> {
  T value;

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

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

}
```

Typecheck under the assumption
? <: T

ETH zürich

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<?> other ) {
    other.value = value;
  }
}
```

Typecheck under the assumption ? <: T

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<?> other ) {
    other.value = value;
  }
}
```

Typecheck under the assumption ? <: T

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<?> other ) {
    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

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

```java
class Random<T> {
  T next( ) { … }

}
```

Java

```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

```
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

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

Upper bound permits covariant instantiation

Use-Site Variance: Covariance

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

```java
class Random<T> {
  T next( ) { … }

}
```

Java

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

Upper bound permits covariant instantiation

Covariant uses typecheck

Use-Site Variance: Covariance

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

```java
class Random<T> {
  T next( ) { … }

}
```
Java

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

Upper bound permits covariant instantiation

Covariant uses typecheck

Use-Site Variance: Covariance

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

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

Java

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

Upper bound permits covariant instantiation

Covariant uses typecheck

ETH zürich

Use-Site Variance: Covariance

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

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

Java

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

Upper bound permits covariant instantiation

Covariant uses typecheck

```java
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

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

Upper bound permits covariant instantiation

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

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

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

Upper bound permits covariant instantiation

Covariant uses typecheck

Contravariant uses do not typecheck

ETH zurich

Use-Site Variance: Contravariance

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

}
```

Java

```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

ETH zürich

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

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

Java

```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( ) );
```

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

Lower bound permits contravariant instantiation

Contravariant uses typecheck

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 ) { … }
  … }
```

```
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

```
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<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 ) { … }
  … }
```

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 );
}
```

```
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<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;
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

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 );
```

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

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

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

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

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

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

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;
}
```

```
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;
}
```

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

Instantiation can change over time

```
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;
}
```

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

Instantiation can change over time

```
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

```
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

```
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

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

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

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

Instantiation is fixed (singleton set)

ETH zürich

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

```
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;
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

```
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 1.4
- 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

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

Java

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

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

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

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

Erasure: Missing Run-Time Information

```java
void foo( Object c ) {
  if( c instanceof Cell<String> )
    …
}
```
Java

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

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

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

```java
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

Erasure: Missing Run-Time Information

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

Java

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

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

Java

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

```java
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#

Run-Time Information for Generics in C#

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

C#

C# can perform dynamic type test

Run-Time Information for Generics in C#

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

C#

C# can perform dynamic type test

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

C#

Run-Time Information for Generics in C#

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

C#

C# can perform dynamic type test

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

C#

C# has run-time representation

Run-Time Information for Generics in C#

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

C#

C# can perform dynamic type test

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

C#

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#

C# can perform dynamic type test

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

C#

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#

C# can perform dynamic type test

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

C#

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#

C# can perform dynamic type test

```
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

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

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

Java

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

Java

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

Java

```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;
}
```

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;
}
```

```
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

No run-time check for generic type

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

ETH zürich

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

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

Java

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

Run-time error: cs.value is not a 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

ETH zürich

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

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

```csharp
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#

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: 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;
}
```

Java:

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

C#:

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

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;
  …
};
```

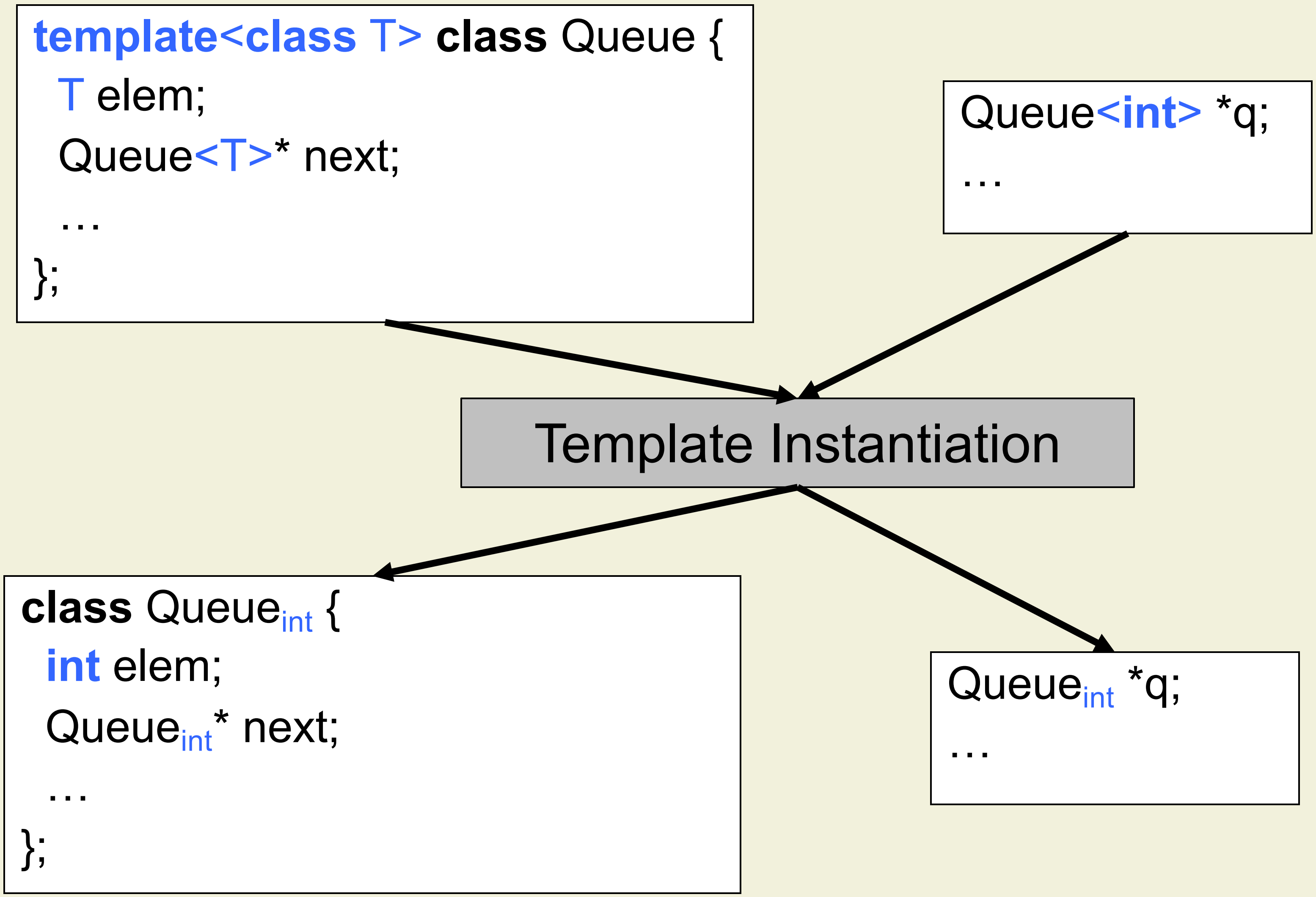
```
Queue<int> *q;
…
```

Template Instantiation

```
class Queue_int {
  int elem;
  Queue_int* next;
  …
};
```

```
Queue_int *q;
…
```

Template Instantiation



Template Instantiation

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

```
Queue<int> *q;
…
```

Compiler generates class for given template instantiation

Template Instantiation

class Queue$_{int}$ {
  int elem;
  Queue$_{int}$* next;
  …
};

Queue$_{int}$ *q;
…

Template Instantiation

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

```
Queue<int> *q;
…
```

Template Instantiation

Compiler generates class for given template instantiation

class Queue$_{int}$ {
  int elem;
  Queue$_{int}$* next;
  …
};

Queue$_{int}$ *q;
…

Client code uses generated class

Template Instantiation

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

```
Queue<int> *q;
…
```

Template Instantiation

Compiler generates class for given template instantiation

```
class Queue_int {
  int elem;
  Queue_int* next;
  …
};
```

```
Queue_int *q;
…
```

Client code uses generated class

Template Instantiation

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

```
Queue<int> *q;
…
```

Compiler generates class for given template instantiation

Template Instantiation

class $\text{Queue}_{\text{int}}$ {
  int elem;
  $\text{Queue}_{\text{int}}$* next;
  …
};

$\text{Queue}_{\text{int}}$ *q;
…

Type checking is done for generated class, not for template

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

```
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

```
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

```
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"; };
};
```

Compiler does not type check template code

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"; };
};
```

Compiler does not type check template code

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"; };
};
```

Compiler does not check availability of methods

Compiler does not type check template code

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"; };
};
```

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

Compiler does not check availability of methods

Compiler does not type check template code

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"; };
};
```

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

Compiler does not check availability of methods

Compiler does not type check template code

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"; };
};
```

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

Compiler does not check availability of methods

Compiler does not type check template code

ETH zürich

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"; };
};
```

Compiler does not check availability of methods

Compiler does not type check template code

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

Compiles even though template is instantiated

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"; };
};
```

Compiler does not check availability of methods

Compiler does not type check template code

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

Compiles even though template is instantiated

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"; };
};
```

Compiler does not check availability of methods

Compiler does not type check template code

```
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( );
```

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"; };
};
```

Compiler does not check availability of methods

Compiler does not type check template code

```
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( );
```

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"; };
};
```

Compiler does not check availability of methods

Compiler does not type check template code

```
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( );
```

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"; };
};
```

Compiler does not check availability of methods

Compiler does not type check template code

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

Compiles even though template 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( );
```

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

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

- Concepts declare syntactic and type constraints

Concepts

```
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 ) {
  { a.compareTo( b ) } -> std::same_as<bool>;
};
```

```
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;
};
```

Template Meta-Programming

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

Template Meta-Programming

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

Template parameters need not be types

Template Meta-Programming

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

Template parameters need not be types

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

Template Meta-Programming

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

Template parameters need not be types

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

Template Meta-Programming

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

Template parameters need not be types

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

Templates can be specialized

Template Meta-Programming

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

Template parameters need not be types

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

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

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

Template parameters need not be types

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

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

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

Template parameters need not be types

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

Templates can be specialized

Compiler generates these instantiations

```
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

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

Template parameters need not be types

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

Templates can be specialized

Compiler generates these instantiations

```
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;
}
```

Through constant propagation, values are computed by compiler

Generic Types vs. Templates: Summary

Generic Types	Templates

Generic Types vs. Templates: Summary

Generic Types

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

Templates

Generic Types vs. Templates: Summary

Generic Types

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

Templates

Generic Types vs. Templates: Summary

Generic Types

- 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

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

Templates

- Type checking per instantiation
  - Flexibility like with structural typing

ETH zürich

Generic Types vs. Templates: Summary

Generic Types

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

Templates

- Type checking per instantiation
  - Flexibility like with structural typing
- No need for run-time support

Generic Types vs. Templates: Summary

Generic Types

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

Templates

- Type checking per instantiation
  - Flexibility like with structural typing
- No need for run-time support

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

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

- Xavier Leroy: *Java Bytecode Verification: Algorithms and Formalizations*. Journal of Automated Reasoning, 2003
- Tim Lindholm, Frank Yellin, Gilad Bracha, and Alex Buckley: *The Java Virtual Machine Specification. 2013* http://docs.oracle.com/javase/specs/
- Gilad Bracha, Martin Odersky, David Stoutamire, and Philip Wadler: *Making the Future Safe for the Past: Adding Genericity to the Java Programming Language*. OOPSLA 1998
- Radu Grigore: *Java Generics are Turing Complete*. POPL 2017