AdaCore
The GNAT Pro Company

A Comparison of Generic Template Support: Ada, C++, C#, and Java™

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Ada europe

VLC VALENCIA
incredible but true

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Correction to Reference in Proceedings Paper

www1.adacore.com/~brosgol/ae2010/examples.html

Missing tilde

Overview

Introduction

Points of comparison

Example: generic stack in Ada, C++, C# and Java

Generic entities and parameters

Constraints on generic formal parameters

Instantiation and implementation model

Generics and Object-Oriented Programming: Covariance and Contravariance

Conclusions

Introduction

Why generics?

- Abstraction from specific data structures/algorithms so that they work for a variety of types
    - Type safety, efficiency
- Seminal work: CLU, Alphard in 1970s

Concepts

- *Generic template*, a language construct (e.g., a type, class, module, or subprogram) parameterized by generic formal parameters
- *Instantiation*: compile-time expansion of template, with arguments replacing generic formals

Typical examples

- Generic container (stack, list, etc) parameterized by element type
- Generic sorting algorithm, parameterized by the element type and comparison function

Workarounds in the absence of generics

- Use of overly general type (`Object`, `void*`), with run-time conversions / type checks
- Macros / preprocessor

But generics are not text macros

- Generic template is checked for syntactic and semantic correctness
- Instantiation is checked (arguments must match generic formal parameters)
- Names in template resolved in scope of template definition, not template instantiation

Generic Instantiation ≠ Text Substitution

Ada

```
package Ada.Text_IO is
   type File_Type is limited private;
   …
   generic
      type Num is mod <>;
   package Modular_IO is
      procedure Put( File : File_Type; Item: Num; …);
      …
   end Modular_IO;
end Ada.Text_IO;
```

```
with Ada.Text_IO; use Ada.Text_IO;
procedure Carpentry_App is
   type File_Type is (Fine, Coarse, Very_Coarse);

   type Byte is mod 256;
   package Byte_IO is new Modular_IO( Byte );
   -- Byte_IO.Put uses Ada.Text_IO.File_Type, not Carpentry_App.File_Type

   B      : Byte := 255;

   File_1 : Ada.Text_IO.File_Type;
   File_2 : File_Type;
begin
   …
   Byte_IO.Put( File_1, B ); -- OK
   Byte_IO.Put( File_2, B ); -- Illegal
   …
end Carpentry_App;
```

Points of Comparison

Expressiveness / basic semantics

- Which entities can be made generic?
- What kinds of formal parameters? Constraints on formal type parameters?
- Rules for instantiation / “contract model”?
- How instantiate: explicit, or implicit?
- Recursive instantiations?

Implementation model

- Expansion-based, or code sharing?
- Any run-time costs?
- When are errors detected?

Feature interactions

- Object-Oriented Programming
  - Inheritance hierarchy for generic types/classes?
  - Covariance/contravariance issue
- Name binding / overload resolution

Example: Generic Stack in Ada

```
generic
    type Element_Type is private;  -- “Constraint”
package Generic_Stack_Pkg is
    type Stack(Max_Size : Natural) is limited private;
    procedure Push(S : in out Stack; Element : in Element_Type);
    procedure Pop (S : in out Stack; Element : out Element_Type);
    generic
       with procedure Display_Element(Element : in Element_Type);
    procedure Display(S : in Stack); -- Display each of the elements
private
   type Element_Array is array( Positive range <> ) of Element_Type;
   type Stack(Max_Size : Natural) is
     record
       Last : Natural := 0;
       Data : Element_Array(1..Max_Size);
     end record;
end Generic_Stack_Pkg;
```

```
package body Generic_Stack_Pkg is …
```

```
with Generic_Stack_Pkg, Ada.Text_IO;
procedure Stack_Example is
  package Integer_Stack_Pkg is new Generic_Stack_Pkg(Integer);
  procedure Put(I : Integer) is …
  procedure Display is new Integer_Stack_Pkg.Display(Put);
  S : Integer_Stack_Pkg.Stack(100);
  N : Integer = 1234;
begin
  Integer_Stack_Pkg.Push( S, Element => N);
  Integer_Stack_Pkg.Push( S, Element => "trouble" ); --Illegal
  Integer_Stack.Display( S );
  N := Integer_Stack.Pop;
end Stack_Example;
```

Example: Generic Stack in C++

```cpp
// stack.hpp
// Inclusion model: template definition in header file
template<typename T>
class stack{
  public:
    const int MAXSIZE;
    stack(int maxsize) : MAXSIZE(maxsize), data(new T[maxsize]), last(-1){ }

    void push(T t){ last++; data[last] = t; }

    T pop(){ T t = data[last]; last--; return t; }

    template<void(*ref)(T)> // "void ref (T)" displays a T value
    void display(){ for (int i=0; i<=last; i++){ ref(data[i]); } }
  private:
    T* data;
    int last;
};
```

```cpp
#include <iostream>
#include "stack.hpp“
extern void put(int i){std::cout << i << std::endl;}

int main() {
  int n=1234;
  stack<int> s(100);
  s.push( n );
  s.push( "trouble" ); // Illegal
  s.display<put>();
  n = s.pop();
}
```

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Example: Generic Stack in C++

```
// stack.hpp
// Inclusion model: template definition in header file
template<typename T>
class stack{
  public:
    const int MAXSIZE;
    stack(int maxsize) ;
    void push(T t);
    T pop();

    template<void(*ref)(T)> // "void ref (T)" displays a T value
    void display(){ for (int i=0; i<=last; i++){ ref(data[i]); } }
  private:
    T* data;
    int last;
};
template <typename T> stack<T>::stack(int maxsize) :
      MAXSIZE(maxsize), data(new T[maxsize]), last(-1){ }
template <typename T> void stack<T>::push(T t){ last++; data[last] = t; }
template <typename T> T stack<T>::pop(){ T t = data[last]; last--; return t; }
```

```
#include <iostream>
#include "stack.hpp“
extern void put(int i){std::cout << i << std::endl;}

int main() {
  int n=1234;
  stack<int> s(100);
  s.push( n );
  s.push( "trouble" ); // Illegal
  s.display<put>();
  n = s.pop();
}
```

Example: Generic Stack in C#

```
public interface IDisplayable{ void Display(); }

// Need to declare a class or struct Int
// in order to ensure that the Display method is available
public struct Int : IDisplayable{
  public int value;
  public Int(int value){ this.value=value; }
  public void Display(){ System.Console.Write(value + " "); }
}
```

```
public class Stack<T> where T : IDisplayable{
  private T[] data;
  public readonly int MAXSIZE;
  private int last=-1;
  public Stack(int maxSize){ MAXSIZE = maxSize; data = new T[maxSize]; }
  public void Push(T t){ last++; data[last] = t; }
  public T Pop(){ T t = data[last]; last--; return t; }
  public void Display(){ for (int i=0; i<=last; i++){ data[i].Display(); } }
}
```

```
public class StackExample{
  public static void Main(){
    int n=1234;
    Stack<Int> stack = new Stack<Int>(100);
    stack.Push( new Int(n) );
    stack.Push( "trouble" ); // Illegal
    stack.Display();
    n = stack.Pop().value;
  }
}
```

Example: Generic Stack in Java

```
public interface Displayable{ void display(); }

public class Int implements Displayable{  // Wrapper class that provides display method
   public int value;
   public Int(int value){ this.value=value; }
   public void display(){ System.out.print(value + " "); }
}
```

```
public class Stack<E extends Object & Displayable>{
   private E[] data;
   public final int MAXSIZE;
   private int last=-1;

   @SuppressWarnings("unchecked")
   public Stack(int maxSize){ MAXSIZE = maxSize; data = (E[])new Object[maxSize]; }
   // Can't create array of E's so we create array of Objects and do unchecked cast

   public void push(E e){ last++; data[last] = e; }
   public E pop(){ E e = data[last]; last--; return e; }
   public void display(){ for (int i=0; i<=last; i++){ data[i].display(); } }
 }
```

```
public class StackExample{
  public static void main(String[] args){
    int n;
    Stack<Int> stack = new Stack<Int>(100);
    stack.push( new Int(n) );
    stack.push( "trouble" ); // Illegal
    stack.display();
    n = stack.pop().value;
  }
}
```

But:

```
public class NastyStackExample{
  public static void main(String[] args){
    int n;
    Stack<Int> stack = new Stack<Int>(100);
    stack.push( new Int(n) );  // OK
    Stack s = stack;           // raw type
    s.push( "trouble" );       // Legal
    n = stack.pop().value;     // Exception
  }
}
```

Generic Entities and Parameters

Ada

Generic units

- Packages
- Subprograms

Generic formal parameters

- Types
- Subprograms
- Objects
- Instances of generic packages

C++

Templates

- Classes and structs
- Functions

Template parameters

- Types
- Constant values (*non-type parameter*)
    - Integral, enumeration, pointer, or reference type
- Templates

C#

Generic entities

- Types
    - Classes, interfaces, structs, delegates
- Methods

Generic formal parameters

- Types

Java

Generic entities

- Classes
- Interfaces
- Methods
- Constructors

Generic formal parameters

- Types

Constraints on Generic Formal Types

Ada

- Numeric type categories
- Discrete types
- Array types
- Access type categories
- Derived types
- Types with assignment, “=”
  - Whether unconstrained objects allowed

C++

No constraints

- If specific operation needed, supply as pointer-to-function generic formal

C#

- Whether reference or value
- Whether it derives from some specific base class or interface(s)
- Whether it has an accessible no-arg constructor

Use reflection to enforce other preconditions

Java

- Whether it extends some specific superclass or implements some specific interface(s)

Use reflection to enforce other preconditions

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Instantiation-Related Issues

Ada

Instantiation always explicit

Legality

- "Contract model"

Expansion / code sharing

- Almost always expansion
- Explicit instantiation provides programmer control over sharing

C++

Instantiation implicit or explicit

Legality

- Constant for non-type parameter
- Argument type may lack operation used by the template (error on usage)

Inclusion or separation model

Expansion / code sharing

- Share instances with same arguments

C#

Instantiation implicit

Legality: parameter matching

Expansion / code sharing

- All instantiations with reference types share single code body
- Instantiations with different value types have separate expansions
- All instantiations with same value type shares same code body

Java

Instantiation implicit

Legality: parameter matching

- Class and interface types only

Expansion / code sharing

- Full code sharing ("type erasure")
- In effect, generic formal parameter replaced by Object or 1st extends bound, and casts are inserted
- All instances share one copy of statics

Covariance and Contravariance

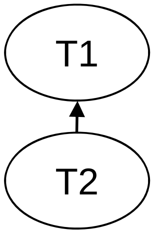
Variance concepts

- Covariance: the ability to use a subclass where a class is required
- Contravariance: the ability to use a superclass where a class is required

Variance in the context of generic types

- Consider a generic type G<T>, parameterized by type T
- If class T2 is a subclass of / derives from T1:
  - Covariance: the ability to use a G<T2> where a G<T1> is required
  - Contravariance: the ability to use a G<T1> where a G<T2> is required

```
G<T1> gt1 = …;
G<T2> gt2 = …;
gt1=gt2; // Covariant
gt2=gt1; // Contravariant
```



```
void  M(G<T1> g1){…}
G<T1> M(){…}
M(gt2);    // Covariant
gt2 = M(); // Contravariant
```

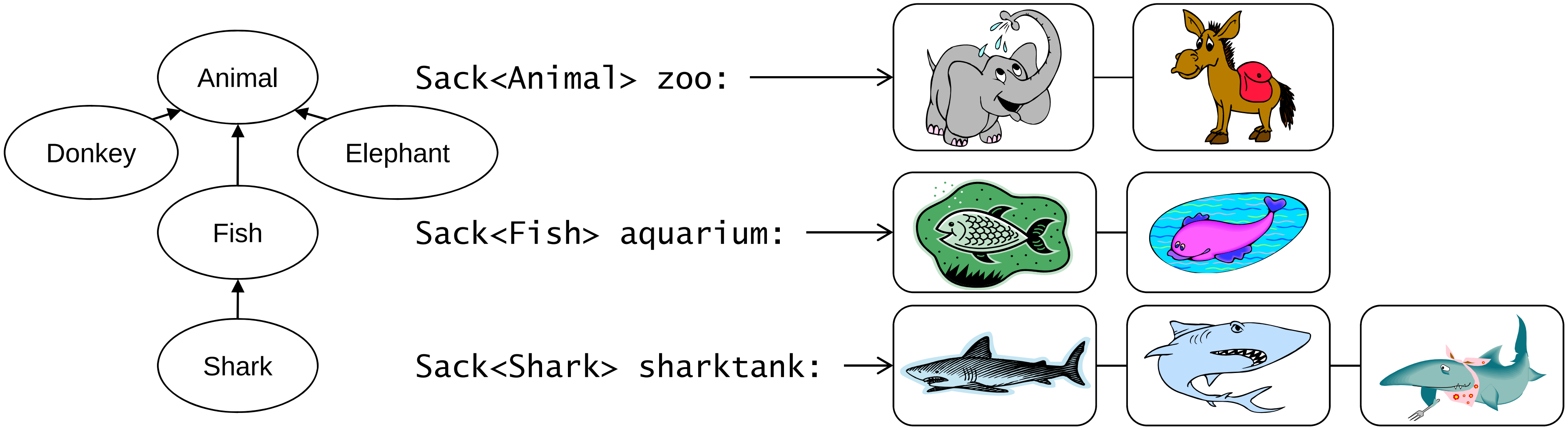
Neither covariance nor contravariance for generics are safe in general

- Example: generic container class Sack<T>, and classes Animal, Fish, Shark
- Assigning a Sack<Fish> to a Sack<Animal> or to a Sack<Shark> could violate type safety

But in some contexts, one or the other may be useful and safe

- Covariance OK if you can only output from gt1 (as a G<T1>) after assigning from gt2
- Contravariance OK if you can only input into gt2 (as a G<T2>) after assigning from gt1

Covariance

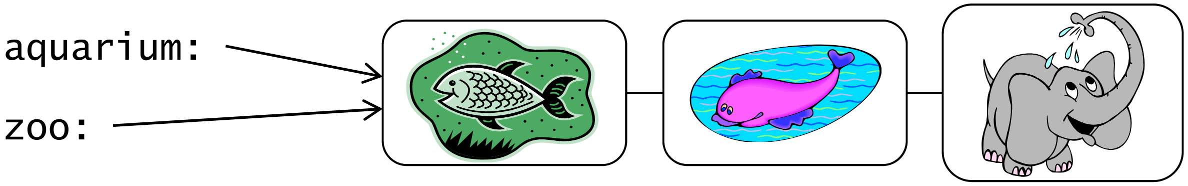


```
Sack<Animal> zoo:
Sack<Fish> aquarium:
Sack<Shark> sharktank:
```

Assignment (for references to objects that are instances of generic types) is not covariant

```
zoo = aquarium; // Covariant?
// If the above were permitted, then the following would be a problem:

Elephant jumbo = new Elephant();
zoo.AddElement( jumbo ); // OK for zoo, but not for aquarium
```

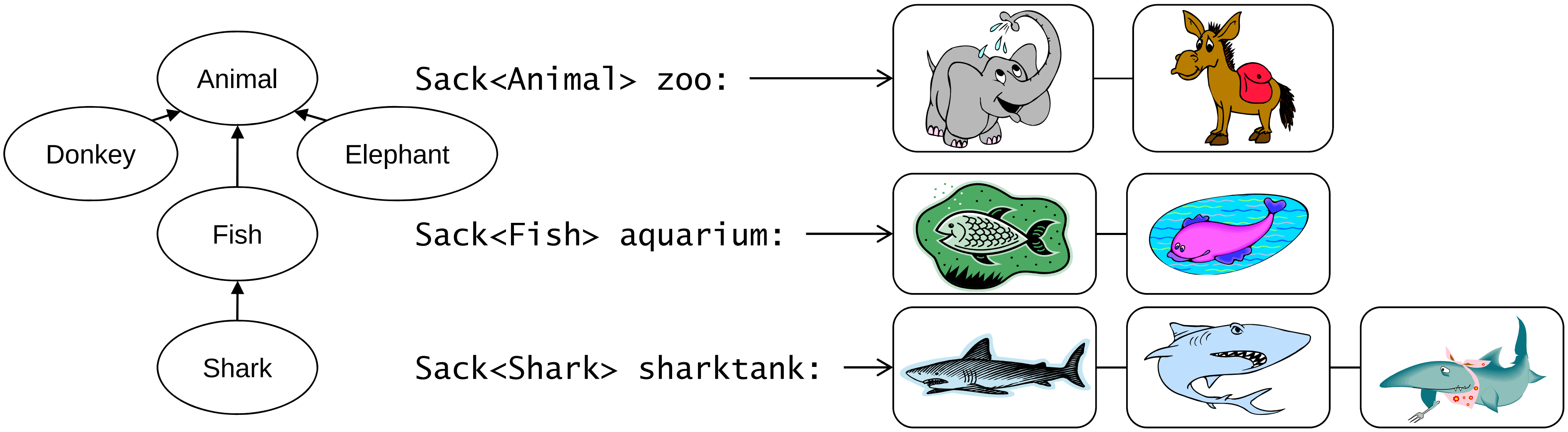


Analogous problem on parameter passing

Assignment could be covariant if there is no way to input Animal objects into zoo afterwards

- For example: reference zoo through an interface that can output but not input elements
    - Thus you can remove elements (as Animal) but not add Animal objects

Contravariance


Animal
Donkey
Elephant
Fish
Shark

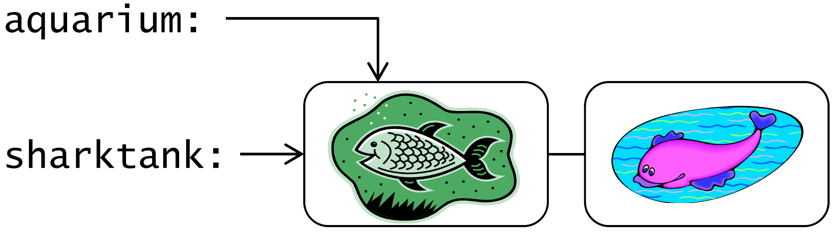
`Sack<Animal> zoo:`

`Sack<Fish> aquarium:`

`Sack<Shark> sharktank:`

Assignment (for references to objects from instances of generic types) is not contravariant

```
sharktank = aquariumm; // Contravariant?
// Obviously unsafe, since could reference a general Fish as a Shark
```


`aquarium:`

`sharktank:`

Assignment could be contravariant if there is no way to output sharktank elements as Shark
- For example: reference sharktank through an interface that can input but not output elements
  - Thus you can add Shark objects but not reference existing elements

Generic Covariance and Contravariance – C#

```
interface IInputable<in T>{
   void AddElement(T t);
}
```

```
interface IOutputable<out T>{
   T RemoveElement();
}
```

```
class Sack<T>:IInputable<T>, IOutputable<T>{
   public void AddElement(T t){…}
   public T RemoveElement(){…}
   …
}
```

```
class Animal{…}

class Fish:Animal{…}

class Shark:Fish{…}

class Elephant:Animal{…}

class Donkey:Animal{…}
```

```
IOutputable<Animal> outzoo;
IInputable<Shark>   insharktank;

Sack<Animal> zoo = new Sack<Animal>();
zoo.AddElement(new Elephant());
zoo.AddElement(new Donkey());

Sack<Fish> aquarium = new Sack<Fish>();
aquarium.AddElement(new Fish());
aquarium.AddElement(new Fish());

zoo    = aquarium;    // Illegal
outzoo = aquarium;    // Covariance
// Can't use outzoo to insert Animals
Animal a = outzoo.RemoveElement(); // OK

Sack<Shark> sharktank;
sharktank   = zoo;   // Illegal
insharktank = zoo;   // Contravariance
// Can't use insharktank to remove Sharks
insharktank.AddElement( new Shark() ); // OK
```

Generic covariance and contravariance are new in C# 4

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Object-Oriented Programming and Generics

Ada

Generic packages may form hierarchy

- Type in child can derive from tagged type in parent

Covariance and contravariance

- Issue does not arise

C++

Class templates may form inheritance hierarchy

Covariance and contravariance are not supported

C#

Generic types may form inheritance hierarchy

Covariance and contravariance

- For interfaces, delegates
- Covariance: “out” type used as method result
- Contravariance: “in” type used as value parameter
- Works only for reference types

Java

Generic types may form inheritance hierarchy

Covariance and contravariance

- Methods can use “wildcards” for parameters, result types
- G<? extends T> allows G<U> where U is a subclass of T (covariance)
- G<? super T> allows G<U> where U is a superclass of T (contravariance)

Conclusions / Distinguishing Features

Ada

- Separation of class into type + module
- Early error detection (“contract model”)
- Most general set of generic formal parameters, constraints on generic formal types

C++

- Deferred error detection
- Flexibility, “metaprogramming”
- Separate compilation issues

C#

- Partial solution to code sharing
- Covariance, contravariance for interfaces and delegates
- Instantiation = IL expansion

Java

- Type erasure / upwards compatibility
  - Anomalies such as shared static data, inability to construct arrays of formal generic type
- Code sharing
- Covariance, contravariance through “wild-cards”