The Cost of Erasure in Java Generics Type System

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ABSTRACT
Java generics, found in versions 1.5 and later, are implemented by generating only one byte code representation of a generic type or method; a compiler maps all the instantiations of a generic type or method to that unique representation via type erasure. The essence of type erasure is the removal during compilation of all information that is related to type parameters and type arguments. From the point of view of the programmer, (s)he is left to negotiate a series of compiler and run-time errors that have little to do with programming errors but a lot to do with the Java generics implementation choice and leaving programmer sometimes with no choice but to live with unclean compiles.

INTRODUCTION
Java generics are implemented by generating only one byte code representation of a generic type or method; a compiler maps all the instantiations of a generic type or method to that unique representation via type erasure. This choice of implementation rises to several rather surprising errors that have nothing to do with programming but only with the consequences of this choice. Beginner Java generics programmers are left to sort out lists of errors which sometimes could not be completely done away with. This may lead to the unpleasant fact that instructors may need to admit that there may be times a clean compile may not be achievable; thus opening a rat’s nest of errors for which a student may unwittingly settle. In this paper we will discuss the consequences of type erasure and provide guidelines for instructors teaching Java generics.

The discussion starts with the basic notions of raw types and compiler error messages; then it proceeds to state the erasure mechanism. It then follows to define reifiable types which have complete runtime type information and discuss their relation to arrays and their component type. The paper then addresses runtime type information method instanceof and casting and their impact on the implementation of equals and clone methods. The paper closes by mentioning other limitations caused by type erasure.

We will assume basic reader’s knowledge of Java’s generics for the definition of a generic interface such as List<T> and two implementations DefaultList<T>, using Vector<T> and LinkedList<T>, which we will use throughout the paper. Consult [3] for details on their implementations. We also assume reader’s knowledge of generic instantiations of a generic type, and of Java’s wildcard type.[1,5]

RAW TYPES
The use and instantiation of a generic type without type arguments is called a raw type. As an example List is called the raw type produced from the type List<T>.

The raw type is the supertype of all its generic instantiations including wildcard instantiations. Assignment of a generic instantiation to its raw type is permitted without warnings; assignment of the raw type to an instantiation yields an "unchecked conversion" warning.

Example (of assignment compatibility):

```java
DefaultList rawList = new DefaultList();
DefaultList<String> stringList = new DefaultList<String>();
rawList = stringList;
stringList = rawList;  // unchecked warning
```

Regarding conversions, the usual reference widening conversion from subtype to supertype is allowed. The reverse is permitted too for reasons of compatibility between generic and non-generic types. It is the so-called unchecked conversion and is accompanied by an unchecked warning. The conversion from the raw type to the unbounded wildcard instantiation is warning-free. (See the implementation of equals below as well.)

It is worth noticing that the raw type List resulting from erasure is not the same as the parameterized type List<Object>; when using the raw type the compiler has no knowledge there are any restrictions on the type of elements allowed to be added by the list; but it lets you insert elements of any type along with a warning to indicate is not type safe: if you insert an element of the wrong type, you may get a ClassCastException at any point in the later execution of the program. But when
List<Object> is used, the compiler knows the list is allowed to contain elements of any type and no such exception will occur.

Raw types exist in Java 1.5 and later for reasons of compatibility with legacy Java code; thus their use should only be considered in these situations. For new Java code such usage should be discourage. Students writing generics code make use of raw types only accidentally and instead of parameterized types; this accidental use results in the mixing of raw types with generic and parameterized types giving rise to untold error warning generated at compilation and which students tend to ignore at their own peril without sorting out the root cause of the warning.

COMPILER MESSAGES

An "unchecked warning" is a warning produced by the compiler to indicate that it cannot ensure type safety. It refers to the fact that the compiler and the runtime system do not have enough type information to perform all type checks that would be necessary to ensure type safety. The most common source of unchecked warnings is caused by the use of raw types because it does not have enough type information to perform all necessary type checks. As an example, consider:

```java
List aL = new DefaultList();
aL.add("abc");   // unchecked warning
```

When add is invoked the compiler does not know whether it is safe to add a String object to the collection; the call is potentially unsafe and an unchecked warning is issued. Unchecked warnings are also reported when the compiler finds a cast whose target type is either a parameterized type or a parameter type as we will see in section 7. You need to resolve warnings due to accidental uses of raw types or else ignore them at your own risk resulting in potential ClassCastException during program execution.

GENERIC TYPES TRANSLATION: TYPE ERASURE

The compiler generates only one byte code representation of a generic type or method and maps all the instantiations of the generic type or method to that unique representation. This mapping is performed by type erasure. The essence of type erasure is the removal of all information that is related to type parameters and type arguments. In addition, the compiler adds type checks and type conversions where needed and inserts synthetic bridge methods when necessary. A bridge method is generated when a type extends or implements a parameterized class or interface and type erasure changes the signature of any inherited method. The steps performed during type erasure include:

*Eliding type parameters:* When the compiler finds the definition of a generic type or method, it removes all occurrences of each type parameter replacing it by its left most bound, or Object if no bound is specified.

*Eliding type arguments:* When the compiler finds a parameterized type, an instantiation of a generic type, it removes the type arguments. For instance, the type List<String> is translated to List.

A side effect of type erasure is that the virtual machine has no information regarding type parameters and type arguments; thus the JVM cannot tell the difference between a List<String> and a List<Date>; therefore we cannot overload a method based on types resulting from different instantiations of the same generic type.

We refer the reader to the appendix for a complete example of code before and after type erasure; for more details on the erasure mechanism see [1,2].

REIFIABLE TYPES

Types that do not lose any information during type erasure are called reifiable types. Because some type information is erased during compilation, not all statically defined types are available at run time. Types that are completely available at runtime are known as reifiable types. The following are reifiable types: non-generic types, non-parameterized types, wildcard parameterized types, raw types, primitive types and arrays of reifiable types.

Array component type

The only allowed types for array creation are: primitive types, non-generic (or non-parameterized) reference types, unbounded wildcard instantiations, and raw types resulting from generic types.

Examples:

```java
int[]   table1 = new int[10];
String[] table2 = new String[10];
List<?>[] table3 = new DefaultList[10];
```
List [] table4 = new DefaultList[10];
What must be noticed is that the component type cannot be parameterized types. Because of type erasure, parameterized types do not have exact runtime type information. Thus, the array store check does not work because it uses the dynamic type information regarding the array's (non-exact) component type. Only arrays with an unbounded wildcard parameterized type as the component type are permitted. More generally, only reifiable types are permitted as component type of arrays.

Also, although you can declare arrays using a type parameter \( T \), or using parametric classes, instances of such arrays are not allowed and will produce compilation errors. Specifically,

```java
1. public class MyContainer<T> {
2.   private T[] elements;
3.   private java.util.Collection<Integer> table;
4.   public Container(int size){
5.     elements = new E[size];
6.     table = new ArrayList<Integer> [size];
7.   }
8. ...
9. }
```

will produce “generic array creation” errors in the lines 5 and 6, where elements and table are created. Since arrays are used to implement collection of objects, we can get around it by creating the arrays having component Object:

```java
public class MyContainer<T> {
    private T[] elements;
...
    public MyComp(int size){
        elements = (T[]) new Object[size];
    }
    ...
}
```

The cast to T[] will produce an unchecked cast warning due to type erasure; but the specification of the List’s add(T element) will guarantee that only elements of type \( T \) will be added to the list. Thus, we will need to live with this warning when using arrays as data components in a generic type implementation.

Why does the code above not generate an ArrayStoreException when elements is accessed? After all, if \( T \) is instantiated with String you can't assign an array of Object to an array of String. Well, because generics are implemented by erasure, the type of elements is actually Object[], because Object is the erasure of \( T \). This means that the class is really expecting elements to be an array of Object anyway, but the compiler does extra type checking to ensure that it contains only objects of type \( T \).

### DYNAMIC TYPE CHECKING AND TYPE CASTING

Due to type erasure the run-time type information is incomplete and some types will result equivalent under runtime typing. For example, recall that getClass, defined in Object and inherited by all classes returns an instance of the class java.lang.Class that models the run-time class of an object. If

```java
List<Student> roll = new DefaultList<Student>();
List<Circle> loops = new DefaultList<Circle>();
```

then

```java
roll.getClass().equals(loops.getClass()) returns true, and both
roll.getClass().toString(), and loops.getClass().toString() return DefaultList.
```

Now, only reifiable types are allowed for instanceof expressions, else a compile-time error is generated; hence, no parametric types are allowed because their dynamic type after type erasure is just the raw type. Examples:

```java
Object obj = new LinkedList<Long>();
System.out.println(obj instanceof List);
System.out.println(obj instanceof List<?>);
```

While those lines are legal, the expressions below will generate errors:

```java
obj instanceof List<Long>
obj instanceof List<? extends Number>
obj instanceof List<? super Number>
```

A cast whose target type is either a parameterized type or a bounded wildcard parameterized type or a type parameter is unsafe. The runtime part of the cast is performed based not on the exact static type, but on the resulting type erasure. In a way, the source code is misleading, because it suggests that a cast to the respective target type is performed, while in fact the
dynamic part of the cast only checks against the type erasure of the target type. The unchecked warning is issued to draw the programmer's attention to the mismatch between the static and dynamic aspect of the cast.

 Occasionally, we would like to cast to a parameterized type, just to discover that the compiler flags it with an unchecked warning. Use of an unbounded wildcard parameterized type instead of a concrete parameterized type or a bounded wildcard parameterized type would help avoid the warning.

A typical example is the implementation of methods such as the equals method, that takes Object reference and were a cast down to the actual type must be performed; another such is the clone method.

**Equals method in a generic class**

Assume we define a generic class Pair with the equals method:

```java
public class Pair<T> {
    private T fst, snd;
    public Pair(T t1, T t2){
        fst = t1;
        snd = t2;
    }
    public boolean equals( Object other) {
        if (other instanceof Pair){
            Pair<T> otherPair = (Pair<T>) other;
            return this.fst.equals(otherPair.fst) && this.snd.equals(otherPair.snd)
        }
        return false;
    }
    //...
}//end class Pair
```

First, note the use of instanceof for the testing of the argument’s type; it uses the raw type Pair and not Pair<T>. It is followed by a parametric cast which will produce an unchecked warning error as the cast target is not a reifiable type. Although the type cast will be incorrect in many cases, when successful it will cast to Pair; the component-wise equality test will catch the different types between components of this and that of otherPair producing the expected false answer when they have different argument type for the generic instantiations; this is the case because every implementation of equals is responsible for performing a check for type matches.

But the program will not compile clean, having the warning error. We can eliminate the warning error by casting using a wildcard argument; in the equals version below we also rewrite the code by not using the instanceof operator but getClass() method to compare the actual runtime class representations:

```java
public boolean equals( Object other) {
    if (this == other) return true;
    if (other == null) return false;
    if (this.getClass() != other.getClass())
        return false;
    Pair<?> otherPair = (Pair<?>) other;
    return this.fst.equals(otherPair.fst) && this.snd.equals(otherPair.snd);
}
```

Only the cast to Pair<?> is accepted without a warning. Note, this technique works only because we need no write access to the fields of the object referred via the wildcard parameterized type. Remember, use of the object that a wildcard reference variable references is restricted. In other situations use of a wildcard parameterized type might not be a viable solution, because full access to the referenced object might be needed.

When implementing the equals method for collections, it is a bit harder to do using the unbounded wildcard casting, although it can be done. It is to note that java.util.collections provides implementations of collections (HashTable, HashSet, etc) where the equality of collections is implemented using a parameterized casting and not an unbounded wildcard casting, hence yielding an unchecked warning error at compilation.

**Clone method and generic classes**

In general one would proceed as it has been the usually common implementation of clone and invoke it on the type components. Unfortunately, you can't call the type parameter clone() because it has protected access in Object, and to call it you have to call it through a reference to a class that has overridden clone() to be public. But the type parameter is not known to re-declare it as public, so this implementation is not workable; thus the implementation of the clone method for generic classes is done via reflection with three caveats.
First, since `super.clone()` returns `Object` we must cast the result to the generic type producing the inevitable unchecked warnings. Likewise, we must cast the result of cloning any fields to the type that the type parameter stands for producing same warnings. Finally, if the generic type has fields that are of a parameterized type and these fields must be cloned then a cast from `Object` to the parameterized type might be necessary and the compiler issues the usual unchecked cast warnings.

Second, we must invoke the fields' `clone()` method via reflection because we do not know whether the respective field has an accessible clone method. This applies to fields of generic types, which for our purposes are unknown. Even if we suspect that the type parameter will be cloneable for purposes of invoking a clone method the `Cloneable` interface is totally irrelevant, thus we cannot be sure the type parameter has a `clone()` method. Hence we must use reflection to find out whether the field has a public clone method. If it has a clone method, we invoke it.

Third, we must deal with exceptions generated by the reflection `getMethod()`. For a generic class we do not know anything about those fields of the class whose type is a type parameter. In particular, we do not know whether those fields are `Cloneable` and/or have a clone method. The attempted invocation of the members' clone method via reflection bears the risk of failure, indicated by a number of exceptions raised by `Class.getMethod` and `Method.invoke` such as `NoSuchMethodException`, `IllegalArgumentException`, etc. In this situation the clone method might in fact fail to produce a clone and it might make sense to indicate this failure by mapping all (or some) exceptions to a `CloneNotSupportedException`.

**WARNING ERRORS DUE TO ERASURE**

Just to summarize, in the use of generics in CS2 there is one unavoidable warning errors in an otherwise clean code. The first one is the type cast needed for an array of `Object` to the desirable one, an array of a generic type parameter; the example was seen on the discussion on array types. The second one is the implementations of `equals` or `clone` for a generic class; this one can be avoided using an unbounded wildcard parameterized type as seen above. Code with raw types will produce warning errors; most likely the use of raw types is accidental as is only needed when mixing legacy code and new generic code.

**Other Erasure casualties**

Here we mention other casualties of type erasure. First, type parameters can't be used in the implements or extends clauses of class definitions. Second, a type must not directly or indirectly derive from two different instantiations of the same generic interface; for instance, a type cannot result from implementing `Comparable<String>` and `Comparable<Number>`, because both of these turn out to be in fact the same interface, `Comparable`, specifying the same `compareTo()` method twice. Third, method overloading using different parameterized types of the same generic type is not legal either. And finally, erasure is also responsible for the lack of construction of type parameter instances as the type is erased; anyway, you can not create an object of generic type because the compiler doesn't know what constructor to call. If your generic class needs to be constructing objects whose type is specified by generic type parameters, its constructors should take a class literal (`MyClass.class`) and store it so that instances can be created via reflection [1,4].

**CONCLUSION**

The use of type erasure for the implementation of generic types as well as parameterized classes leave these classes in an incomplete state with respect to runtime type information; in fact, erasure makes a hole in the Java’s type system. The result is a performance hit due to the added casts and possible bridge method calls performed by the compiler, and lost of type safety. And because of the fact that at runtime the type safety of many operations cannot be fully checked, java’s compiler generates warning errors that gives the programmer the option to ignore them at their own peril; they can produce later on a `ClassCastException` when the runtime system performs the cast expected to the type used by the given generic instantiation.

Students should be alerted to the sources of these warnings and the need to sort out each of them for actual elimination to a possible few as mentioned in the paper.

**REFERENCES**

[4] Sun Corporation. Java API for version 1.5 or later.
Appendix

An example of code before type erasure follows:

```java
interface Comparable <T> {
    public int compareTo( T that);
}
class NumericValue implements Comparable<NumericValue>{
    private byte value;
    public NumericValue (byte value) {this.value = value; }
    public byte getValue() { return value; }
    public int compareTo( NumericValue that) { return this.value - that.value; }
};//end Numeric Value
class Collections {
    public static <T extends Comparable<? super T>> T max(Collection <T> xs) {
        Iterator <T> xi = xs.iterator();
        T w = xi.next();
        while (xi.hasNext()) {
            T x = xi.next();
            if (w.compareTo(x) < 0) w = x;
        }
        return w;
    }
};//end Collections
class Test {
    public static void main (String[] args) {
        LinkedList <NumericValue> numberList = new LinkedList <NumericValue> ();
        numberList.add(new NumericValue((byte)0));
        numberList.add(new NumericValue((byte)1));
        NumericValue y = Collections.max( numberList );
    }
}
```

Example of the code resulting from type erasure follows.

```java
interface Comparable {
    public int compareTo( Object that);
}
class NumericValue implements Comparable {
    private byte value;
    public NumericValue (byte value) { this.value = value; }
    public byte getValue() { return value; }
    public int compareTo( NumericValue that) { return this.value - that.value; }
    public int compareTo(Object that) { //bridge method added by compiler
        return this.compareTo((NumericValue)that);
    }
} 
class Collections {
    public static Comparable max(Collection xs) {
        Iterator xi = xs.iterator();
        Comparable w = (Comparable) xi.next();
        while (xi.hasNext()) {
            Comparable x = (Comparable) xi.next();
            if (w.compareTo(x) < 0) w = x;
        }
        return w;
    }
} 
class Test {
    public static void main (String[] args) {
        // same first 3 lines
        NumericValue y = (NumericValue) Collections.max( numberList );
    }
} 
```

The generic Comparable interface is translated to a non-generic interface and the unbounded type parameter T is replaced by Object. NumericValue class implements the non-generic Comparable interface after type erasure; the compiler adds a bridge method, compareTo with Object as parameter, so that NumericValue still implements Comparable. In max, the bounded parameter T is replaced by its left most bound, Comparable. Iterator<T> is translated to Iterator and the compiler adds a cast whenever an element is retrieved via the iterator. Uses of LinkedList<NumericValue> and generic max in the main method are translated to uses of the non-generic type and method and, again, the compiler must add a cast back to NumericValue where needed.