COMP 110/401

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17. Inheritance

Inheritance in an object-oriented language is not much different than inheritance in the real world. Just it is possible to automatically inherit money from a benefactor or genes from ancestors, it is possible to inherit code from an object type – specifically the methods and variables defined by that type.

The idea of inheritance is related to the IS-A relation. Again, this relation is used in the non computer world. A human is a mammal; a salmon is a fish; and each of you is a student. Similarly, we say that ACartesianPointy is a Point because it implements Point. We will see that inheritance, like interface implementation, is also an is-a relation. We will show how type checking of object variables is based on this relation.

In this chapter, we will mainly use collections to illustrate and motivate inheritance and the is-a relation. We have seen how we can create certain kinds of sequences, such as histories and databses, using arrays. Some of these types can be considered as special cases of other types. We will see how a specialized type can inherit the code from a more general type much as a child inherits genes from a parent.

Inheritance

We have seen two kinds of collections created using arrays, a history and a database. A history is defined by the interface, `StringHistory` and implemented by the class, `AStringHistory`; while a database is defined by the interface, `StringDatabase`, and implemented by the class `AStringDatabase`. Figure 1 shows the members (methods and instance variables) declared in the interfaces and classes.

Let us compare the database class and interfaces with the history class and interface. The database interface defines all the methods of the history interface, plus some more. In other words, *logically*, it is an "extension'' of the history interface, containing copies of the methods `elementAt`, `addElement`, and `size`, and adding the methods, `deleteElement`, and `clear`. Similarly, logically, the database class is an extension of the history class, in that it contains a copy of all of the members defined in the latter – the `size` and `contents` instance variables, and the `addElement`, `size`, and `elementAt` instance methods. As a result, `AStringDatabase` implements a superset of the functionality of `AStringHistory`. However, *physically*, the database interface and class are not extensions of the

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history interface and class, because they duplicate code in the latter – each member of the history interface/class is re-declared in the database interface/class.

In fact, Java allows us to create logical interface and class extensions as also physical extensions. The database interface can share the declarations of the history interface as shown here:

```
public interface StringDatabase extends StringHistory {
      public void deleteElement(String element);
      public void clear();
      public boolean member(String element);
}
```

The keyword **extends** tells Java that the interface `StringDatabase` is a physical extension of `StringHistory`, which implies that it implicitly includes or *inherits* the constants and methods declared in the latter. As a result, only the additional declarations must be explicitly included in the definition of this interface.

Below, we see how the database class can share the code of the history class:

```
public class AStringDatabase
                  extends AStringHistory implements StringDatabase {
      public void deleteElement(String element) { … }
      int indexOf(String element) { … }
      void shiftUp(int startIndex) { … }
      public boolean member(String element) { … }
      public void clear() { … }
}
```

The method bodies are not given here since they are the same as we saw earlier. The important thing to note here is that the class does not contain copies of the methods and instance variables declared in `AStringHistory` because it now (physically) extends it.

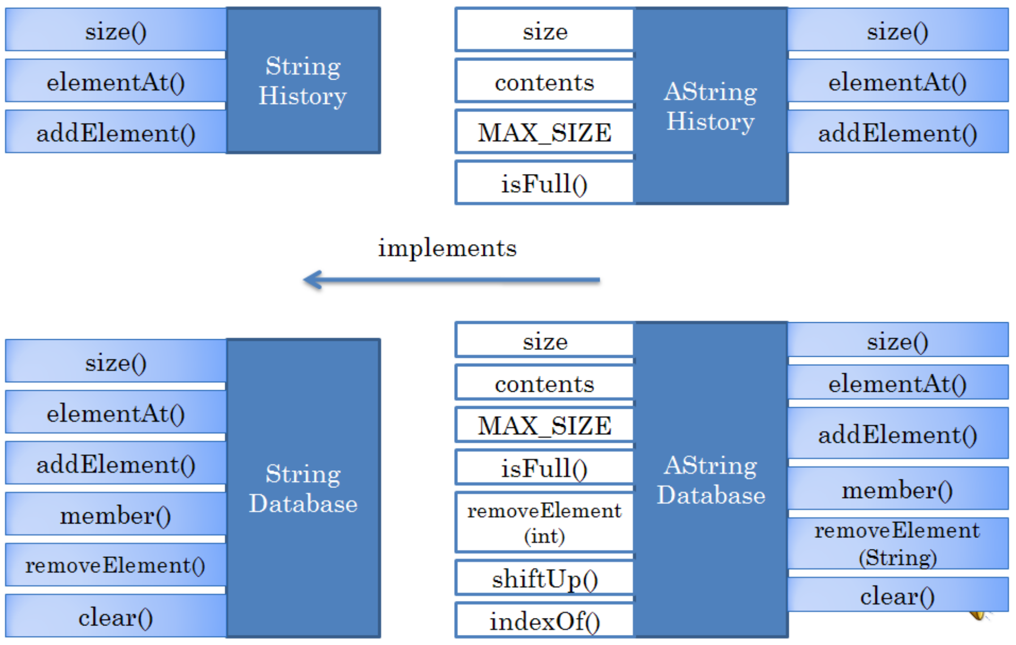


Figure 1. Logical but not physical extensions

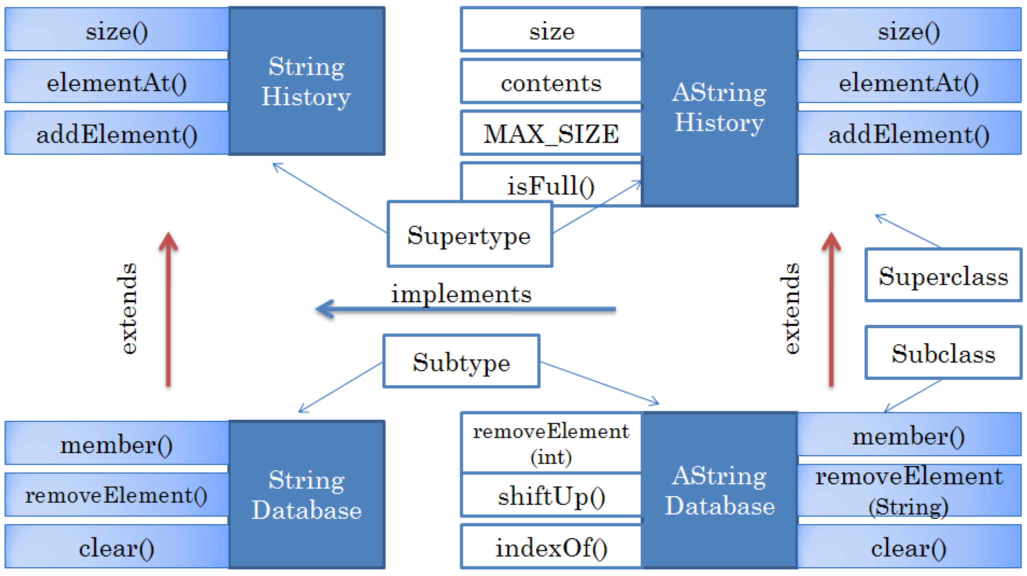


Figure 2. Physical and logical extensions

Given an interface or class, A, and an extension, B, of it, we will refer to A as a *base* or *supertype* of B; and to B as a *derivation, subtype,* or simply *extension* of A (

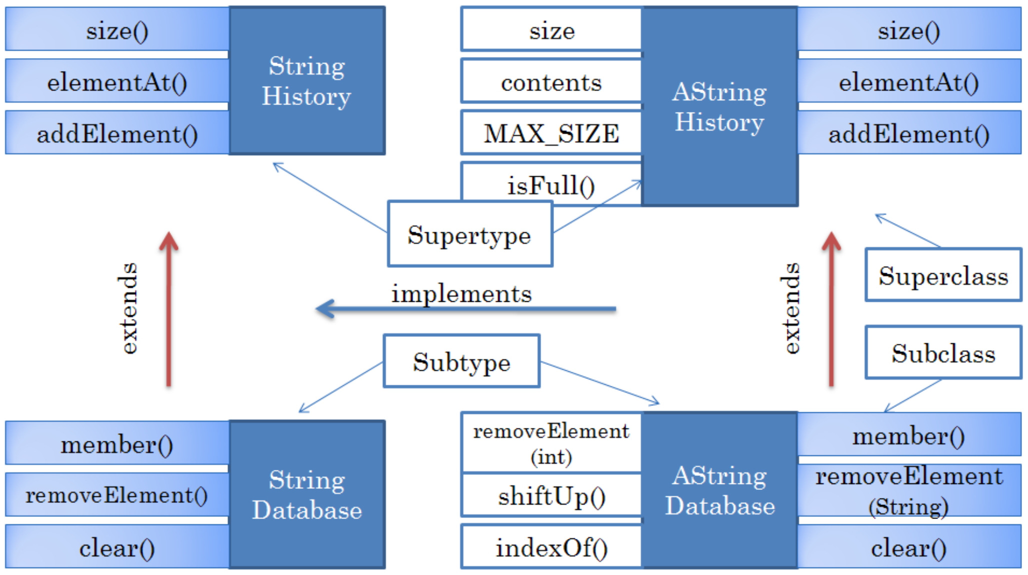


Figure 2).

Any class that implements an extension of an interface must implement all the methods declared in both the extended interface and the extension. Thus, in our example, `AStringDatabase` must implement not only the methods declared in `StringDatabase`, the interface it implements, but also the ones declared in the interface, `StringHistory`, the interface extended by `StringDatabase`. Thus, the new definition of `StringDatabase` and `AStringDatabase` are equivalent to the ones given before.

Why Inheritance?

There are several reasons for extending interfaces and classes, as we have done above, rather than creating new ones from scratch, as we did before:

- *Reduced Programming/Storage Costs*: The most obvious reason is that we do not have to write and store on the computer a copy of the code in the base type, thereby reducing programming and storage costs. The programming cost, of course, is minimal if we had a convenient facility to cut and paste. However, the source code of the base type may not always be available, which does not prevent it from being sub typed.

- *Easier Evolution*: Code tends to change. We may decide to change the `MAX_SIZE` constant of `AStringHistory`, in which case, would have to find and change all other classes that are logical but not physical extensions.

- *Polymorphism*: Inheritance allows us to support new kinds of polymorphism, as explained below.

- *Modularity*: We assume above that the base class and interface already existed when we created subclasses of them. For instance, we assumed first that we needed string histories and created appropriate interfaces and classes to support them. Later, when we found the need for string databases, we simply extended existing software. What if we have not had the need for string histories, and were told to create string histories from scratch? Even in this case, we may want to first create string histories and then extend them rather than create unextended string databases, because the extension approach increases modularity, thereby giving the accompanying advantages. In this example, it makes us understand, code, and prove correct the two interfaces and classes separately. Moreover, if we later end up needing string histories, we have the interface and class for instantiating them. The approach requires us to *design for reuse,* something that is very difficult to do in practice.

Inter-Type Reuse Rules

In general, knowing when to use inheritance requires some experience. A simple rule of thumb is that if there is code duplication in different types (interfaces/classes), then you should think either of inheritance or delegation, which we will study later. (Intra-type code duplication involves two methods within the same class duplicating code, and is removed by putting the common code in a common method called by both methods.)

Our previous version of StringDatabase duplicated all the method headers in StringHistory. By examining the two interfaces, it was pretty straightforward to reduce this code duplication by making StringDatabase a subtype of StringDatabase. In the previous versions of AStringHistory and AStringClasses had even more code duplication, as not only were public method headers duplicated in these classes, but also the bodies of these methods, and the variables and non public method accessed by these methods. Again, it was pretty straightforward to reduce the code duplication by making AStringDatabase a subtype of AStringHistory.

This example leads us to our first re-use rule: Use inheritance (and/or delegation) to get rid of method header/body duplication in different types (interfaces/classes).

This rule is not sufficient to eliminate duplication because the same abstract operation can be associated with different method headers. For instance, the addElement() method in (a) StringHistory and AStringHistory could have been called addToHistory(), and (b) StringDatabase and AStringDatabase could have been called addToDatabase().

This leads us to the second code re-use rule: Ensure that conceptual operations with the “same” semantics (behavior) are associated with same method headers in different types (interfaces/classes).

The term “same” is in quotes because it requires some subjective interpretation, especially in an interface. An interface only gives the method header of an operation – the body of the method is provided by a class that implements the header. It is possible, and in fact, often expected, for two different classes to provide different implementations of the header. Thus, “same” behavior does not mean “identical” behavior. Similarly, as we will see when we see the implementation of addElement() in AStringHistory, this method does an extra check that is not performed by the addElement() of AStringHistory() and AStringDatabase(). Yet this operation is the same in all three collections as at an abstract level, it adds an element to a collection. This is why the rule says that the “conceptual”

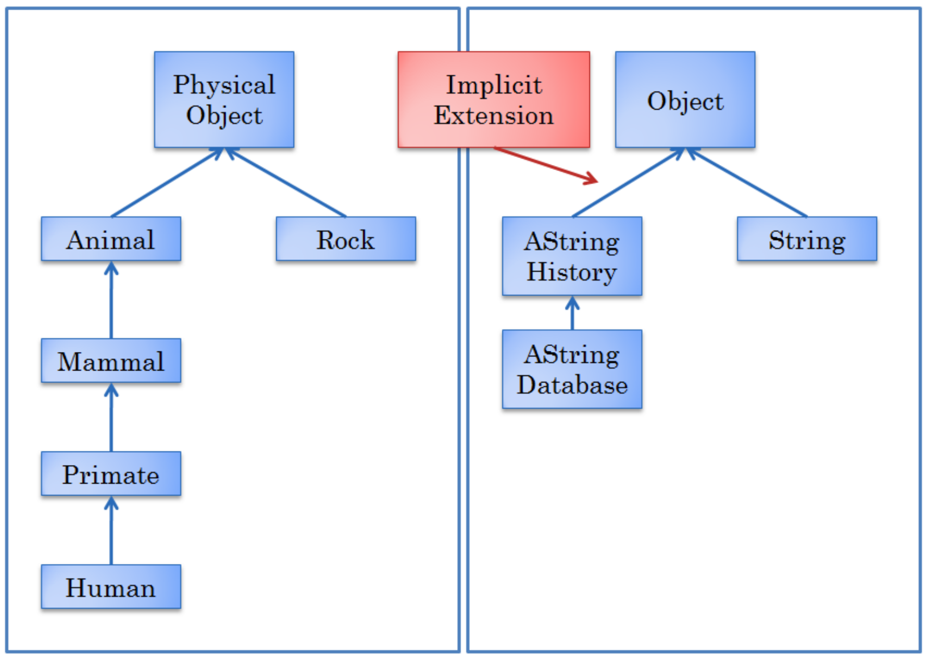


Figure 3. Logical but not physical extensions

operation rather that the exact operations should be the same. It is in the interpretation of this rule where experience really helps.

Real-World Inheritance

Programming using objects, classes, and inheritance is called an *object-oriented programming*. In contrast, a programming using only objects and classes is called *object-based programming*. Thus, with the use of inheritance, we are making a transition from object-based programming to object-oriented programming.

Let us go back to the real-world analogy to better understand inheritance and why it is important. Often physical products are extensions of other physical products. For instance, a deluxe model of an Accord has all the features of a regular model, and several more such as cruise control. When specifying the deluxe model, it is better to create an addendum to the existing specification of a regular model, rather than create a fresh specification. As a result, if we later decide to update the specification of a regular model, we do not have to go back and update the specification of the deluxe model, which is always constrained to be an extension of a regular model.

Similarly, we may want to implement an extended interface by extending a factory, rather than creating a new factory. For instance, when we need to create a deluxe model, we may first send it to a factory that creates a regular model, and then add new features to this model.

We do not have to look at the man-made world for examples of these relationships. For instance, as shown in Figure 3, a human is a primate, which is a mammal, which is an animal, which is a living organism, which is a physical object; and, a rock can be directly classified as a physical object. Thus, both a human and a rock inherit properties of physical objects – for instance, we can see, touch, and feel them.

Thus, like objects and classes, inheritance feels "natural" and allows us to directly model the inheritance relationships among physical objects simulated by the computer. For example, we could model a human being as an instance of a `Human` Java type, which would be a subtype of `Primate`, and so on. Without inheritance, we would have to manually create these relationships.

The Class Object

Just as, in the real world, we defined the group, `PhysicalObject`, to group all physical objects in the universe and define their common properties, Java provides a class, *Object,* to group all Java objects and define their common methods. It is the top-level class in the inheritance hierarchy Java creates for classes (Figure 3). If we do not explicitly list the superclass of a new class, Java automatically makes `Object` its superclass. Thus, the following declarations are equivalent:

```
public class AStringHistory implements StringHistory
```

and

```
public class AStringHistory extends Object implements StringHistory
```

The methods defined by `Object`, thus, are inherited by all classes in the system. An example of such a method is `toString`, which returns a string representation of the object on which it is invoked. The implementation of this method in class `Object` simply returns the name of its class followed by an internal address (in hexadecimal form) of the object. Thus, an execution of:

```
System.out.println((new AStringHistory()).toString())
```

might print:

```
AStringHistory@1eed58
```

while an execution of:

```
System.out.println((new AStringDatabase()).toString())
```

might print:

```
AStringDatabase@1eed58
```

where “leed58” is assumed to be the internal address of the object in both cases. In fact, we did not need to explicitly call `toString` in the examples above. `println` automatically calls it when deciding how to display an object. Thus:

```
System.out.println(new AStringDatabase))
```

is, in fact, equivalent to:

```
System.out.println((new AStringDatabase()).toString())
```

`Object` defines other methods, which we will not study here, which can also be invoked on all Java objects.

Despite its name, `Object` is a class, and not an instance. It defines the behavior of a generic Java object, hence the name.

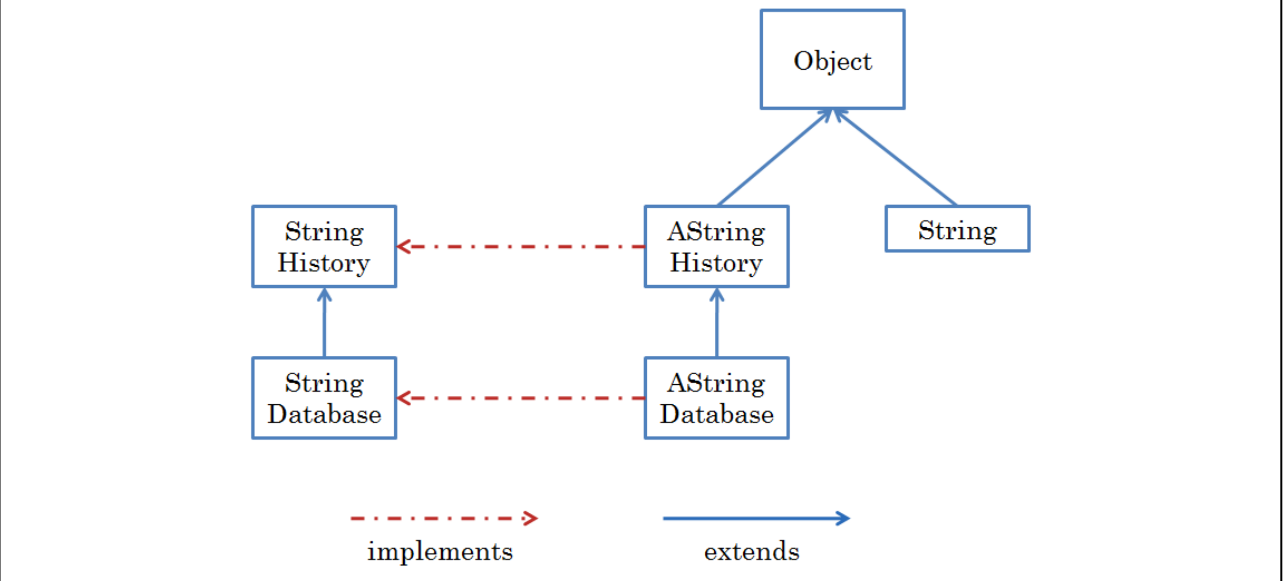
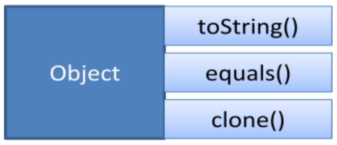


Figure 4. IS-A Relationship

It defines a variety of methods, three of which, shown in the figure below, we will look in some depth later.



The class Object does not implement any interface. Not only is this bad design, according to our rule that every class must implement one (or more) interfaces, but it raises some conceptual problems in variable assignment, as we will see below.

IS-A Relationships

An inheritance relationship between a subtype and a supertype is a special case of the more general IS-A relationship among entities. Intuitively, we might say:

AStringDatabase IS-A AStringHistory

This assertion seems right since a string database is also a string history. In ordinary language, we say some entity e1 IS-A e2 if e1 has all the properties of e2. Thus, a primate is a mammal since it has all the properties of a mammal. In the context of an object-oriented programming language, the entities are object types (classes and interfaces) and their instances (objects), and the properties we use to determine IS-A relationships among them are their public members (methods and variables).

We can now formally define the IS-A relationship among Java object types and their instances. Given two object types, T1 and T2, and arbitrary instances t1 and t2 of these types, respectively:

T1 IS-A T2

is true if

t1 IS-A t2

is true, which in turn, is true, if all public members of t2 are also public members of t1.

From this definition, we can derive, that:

T2 extends T1 => T2 IS-A T1

because every instance of T2 has not only the members declared in its type T2, but also all members declared in the super type of T2, T1. The reverse is not true:

T2 extends T1 => T1 IS-A T2

since T2 can define additional public variables and methods that instances of T1 do not have.

Inheritance is only one example of an IS-A relationship. The implements relationship between a class and an interface is another example:

T2 implements T1 => T2 IS-A T1

because every instance of T2 has all the members defined in T1 (plus, optionally, some more since a class is free to define public members not declared in its interface).

Thus, some IS-A relationships defined by Figure 4 are:

StringDatabase IS-A StringHistory
AStringDatabase IS-A AStringHistory
AStringHistory IS-A StringHistory
AStringDatabase IS-A StringDatabse

In other words, each of the arrows in the figure denotes an IS-A relationship. Figure 4 shows both inheritance and implements forms of IS-A relationships among some of the classes and interfaces we have seen.

The IS-A rule is transitive:

T3 IS-A T2 IS-A T1 => T3 IS-A T1

This follows from transitivity of the inheritance relationship. Thus:

AStringDatabase IS-A StringHistory

By our definition, it is also reflexive:

T1 IS-A T1

Thus:

AStringHistory IS-A AStringHistory

which should not be surprising!

Type Rules

The IS-A relationship gives the basis for type-checking rules in Java. Consider the following declarations:

```
StringHistory stringHistory = new AStringDatabase();
StringDatabase stringDatabase = new AStringHistory();
```

They assign to variable of type T1 an object of another type T2. Should these be allowed?

In the first case, we are trying to assign an instance of `AStringDatabase` to a variable expecting `StringHistory`. Since:

```
AStringDatabase IS-A StringDatabase IS-A StringHistory
```

the assignment is legal. On the other hand, in the second case we are trying to assign an instance of `AStringHistory` to a variable expecting `StringDatabase`. Since `AStringHistory` is not, directly or indirectly, `StringDatabase`, the second assignment is illegal.

To understand what may go wrong in the second assignment, consider the following operation invocation:

```
stringDatabase.clear();
```

Because the type of `stringDatabase` is `StringDatabase`, this invocation will be considered legal at compile time. However, if `stringDatabase` is actually assigned an instance of `AStringHistory`, the instance will not have the `clear` member, and we will get a runtime error.

To understand why the first assignment is safe, consider an operation invocation on `stringHistory`:

```
stringHistory.size();
```

If `stringHistory` has been actually assigned an instance of `AStringDatabase`, the instance is guaranteed to have all the publically accessible members of an instance of `StringHistory`, since indirectly `AStringDatabase` IS-A `StringHistory`.

Given the first assignment:

```
StringHistory stringHistory = new AStringDatabase();
```

should the following be legal?

```
stringHistory.clear();
```

Since `stringHistory` has been assigned an instance of `AStringDatabase`, the instance will have the member, `clear`. However, the compiler will complain. This is because, at compile time, we do not know the exact value of a variable, and have to take the conservative approach of assuming it has only those members that are indicated by its type (and no other member). However, if, at runtime, we are sure about the actual type of the object, we can use a cast, as shown below:

```
((StringDatabase) stringHistory).clear()
```

The cast assures the compiler that the type of the object stored in `stringHistory` is actually `StringDatabase`. Unlike other languages such as C that allow casting, Java keeps the type of a variable at runtime, and will throw an exception if the actual type, T2, does not match the type, T1, given in the cast, that is T2 is not a T1. Thus, if we executed:

```
stringHistory = new AStringHistory();
((StringDatabase) stringHistory).clear()
```

we would get a `ClassCastException`.

We can now precisely state the complete type rules used by the compiler. Assume we assign to some variable v of type T1 an expression e of type T2. T1 and T2 may be interfaces, classes, or primitive types. The assignment is legal if either of the two conditions holds true:

- T2 IS-A T1
- T2 IS-NARROWER-THAN T1

where the narrow relationship was defined in the chapter on types.

Typing an expression is ambiguous if a cast is used:

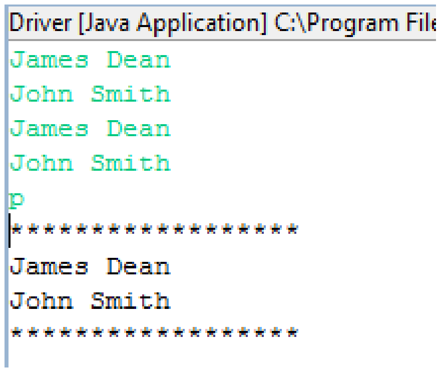
```
(StringDatabase) stringHistory
```

A cast creates two types for the expression being cast: a static type and a dynamic type. The *static type* is the type used for cast. Thus in the above example, `StringDatabase` is the static type of the expression. The *dynamic type* is the actual type of the expression being cast, which is determined at runtime. Thus, in the above example, it is determined by the object that has been assigned to `stringHistory`. The type checking rules above use the static type at compile time. A separate type-checking phase occurs at runtime, which uses the actual type, T2 of the cast expression to ensure it is compatible with static type, T1, used for casting, that is, T2 IS-A T1, as discussed above.

To understand these type rules intuitively, let us consider again the real world. The following is legal:

```
ARegularModel myCar = new ADeluxeModel();
myCar.accelerate();
```

If our rental or buying plan assumes a regular model, and we are upgraded to deluxe model, that is safe, because all operations on a regular model such as accelerate are also applicable on a deluxe model. However, the following is not legal:



```
Driver [Java Application] C:\Program File
James Dean
John Smith
James Dean
John Smith
p
******************
James Dean
John Smith
******************
```

Figure 5. AStringSet

```
	ADeluxeModel myCar = new ARegularModel();
	myCar.setCruiseControl();
```

If our plan assumes a deluxe model, and we are downgraded to a regular model, we will be unhappy, and potentially unsafe, because some operations such as `setCruiseControl` are applicable only to deluxe models. However, the following is safe:

```
	ARegularModel myCar = new ADeluxeModel();
	ADeluxeModel hisCar = (ADeluxeModel) myCar;
```

In other words, we should be able to perform operations of the upgrade that could not be performed on the car we reserved, as long it can be assured that we did indeed get an upgrade, that is, the cast is successful.

Thus, compile-time type checking is equivalent to checking that our plan for driving the car is consistent with the car we have reserved, while runtime checking is equivalent to checking that it is consistent with the actual car we obtained. It is important to note that both checks occur before we use the car in an inappropriate way, for instance, before we actually try to set the cruise control.

Inheritance and Polymorphism

A consequence of our type rules is that the method we defined for printing `StringHistory`:

```
	static void print(StringHistory strings) {
		System.out.println("******************");
		int elementNum = 0;
		while (elementNum < strings.size()) {
			System.out.println(strings.elementAt(elementNum));
			elementNum++;
		}
		System.out.println("******************");
	}
```

will also work for printing instances of `StringDatabase`. That is, we can safely invoke:

```
        print(stringDatabase);
```

This is because the following assignment is made during parameter passing:

```
        StringHistory strings = stringDatabase;
```

which is allowed by the assignment rules. The only member of the argument accessed by `print` is `elementAt`, which is also a member of `stringDatabase`.

Recall that a method such as `print` that takes arguments of multiple types is called polymorphic. Recall also that creating IS-A relationships via the implements relationships allowed us to write such methods. Here we see that creating IS-A relationships through inheritance also supports such methods. The type checking rules described above have been designed to support polymorphism.

Mixing the class Object and Interfaces*

Consider the following statements:

```
StringHistory stringHistory = new AStringHistory();
Object object = stringHistory;
```

Should the second statement be allowed? Intuitively, the answer is yes, as every value assigned to a variable is an Object. Yet, interestingly, our type and IS-A rules do not allow this statement. Our assignment rules say that this statement is legal as long as StringHistory, the type of the RHS (right hand side) IS-A the type of the LHS (left hand side) of the assignment. Our IS-A rules in, turn, say that StringHistory IS-A Object as long as StringHistory (directly or indirectly) extends the class Object. But an interface cannot (directly or indirectly) extend a class!

Java does allow the assignment of an objects typed using an interface to a variable of type Object. To support this feature, it adds an extra rule to the IS-A definition which says T IS-A Object, for all types T. Had Object implemented an interface, there would be no need for this extra rule.

The following example shows a practical situation in which an object typed using interface are assigned to variables typed as Object:

```
StringHistory stringHistory = new AStringHistory();
System.out.println(stringHistory);
```

The type of the formal argument of the println() method called in the second statement is of type Object. Here we are assigning to this variable typed using an interface. You will encounter several examples of such assignment.

Overriding Inherited Methods and super Calls

Returning to the database application, suppose we did not want to print or store duplicates in the database, and instead wanted the output shown in Figure 5. To support this application, we need the collection to behave like a mathematical (ordered) set, which allows no duplicates. To define such a collection, we do not need to add to the operations we defined for a database. Instead we can simply re-implement the `addElement` operation inherited from `AStringHistory` so that does not add duplicates to the collection:

```
public    class    AStringSet    extends    AStringDatabase    implements
StringDatabase {
      public void addElement(String element) {
            if (member(element)) // check for duplicates
                  return;
            // code from AStringHistory
            if (isFull())
                  System.out.println("Adding item to a full history");
            else {
                  contents[size] = element;
                  size++;
            }
      }
}
```

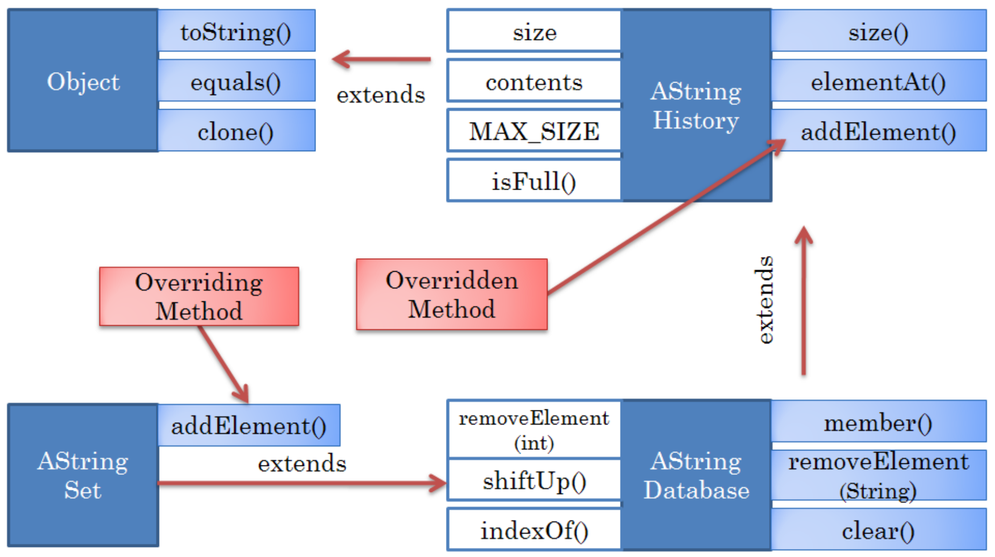
What we have done here is to replace or *override* an inherited method implementation.

In the above implementation, we duplicated the code for adding an element to the collection. The following implementation fixes this problem:

```
public    class    AStringSet    extends    AStringDatabase    implements
StringDatabase {
      public void addElement(String element) {
            if (member(element)) // check for duplicates
                  return;
            // code from AStringHistory
            super.addElement(element);
      }
}
```

Here, we directly invoke the addElement() method in the superclass AStringHistory rather than execute a copy of its code. In general, when we use the keyword **super** in a class C as a prefix to a method call, we ask Java to follow the super class chain of C to find the first class with a definition that matches the method call, and invoke that method. The super class chain of C_1, C_2, .. Object, where C_{i+1} is the super class of C_i and C_1 is the super class of C. Thus, the super class chain of AStringSet is AStringDatabase, AStringHistory, Object. When **super**.addElement(element) method invoked by AStringSet, Java first checks if a matching definition is provided by AStringDatabase. As it is not, it then goes to the next super class in the chain, AStringHistory, and performs the same check. As it does find a definition this time, it uses it and does not look further up the chain. The matching method definition can be found at compile time – there is no need to wait until execution time to resolve the call.

In the implementation of AStringSet, we have not implemented a new interface, only provided a new implementation of an existing interface, `StringDatabase` by overriding one of the inherited methods. The notion of overriding is shown pictorially in the following figure.



To implement the above application, the main method remains the same as the one we used for the database application, except that we replace the line:

```
    StringDatabase names = new AStringDatabase();
```

with:

```
    StringDatabase names = new AStringSet();
```

When the `addElement` method is invoked on `name`:

```
    names.addElement(input);
```

the implementation defined by the class of the assigned value (`AStringSet`) is used since it overrides the inherited implementation of the operation from `AStringDatabase`.

The above collection does not completely model a Mathematical set in that it does not define several useful set operations such as union, intersection, and difference, which we did not need in this problem. Question 6 motivates the use of a more complete implementation of a set.

Inheritance among Geometric Classes

We have used inheritance above to reuse code in related collections. In fact, it can be used in almost any application. In particular, it is useful to reuse code among different geometric classes, as is demonstrated in depth in the exercises. Here is a simple example to make this point:

```
public class ABoundedPoint extends ACartesianPoint implements BoundedPoint {
   Point  upperLeftCorner, lowerRightCorner;
   public ABoundedPoint (int initX, int initY,
          Point initUpperLeftCorner, Point initLowerRightCorner) {
          super(initX, initY);
          upperLeftCorner = initUpperLeftCorner;
```

```
            lowerRightCorner = initLowerRightCorner;
        }
        public Point getUpperLeftCorner()  {upperLeftCorner }
        public  void setUpperLeftCorner(Point newVal) {
                upperLeftCorner = newVal;
         }
        public  void setX(int newX} {
                if (newX >= upperLeftCorner.getX() && newX <= lowerRightCorner.getX) {
                      super.setX(newX);
        }

       …
      }
}
```

This class creates an extension of ACartesianPoint that confines the point to a rectangular region whose upper and lower right corners are defined by two properties. The exact semantics of the class do not matter – this is the reason why the implementation of the methods of this class is not given. What is important is that this class inherits the instance variables of the super class and can override methods to ensure that the point cannot be moved outside the associated rectangle. Like AStringSet, it uses the **super** keyword to call a method in the superclass.

```
super.setX(newX);
```

In addition, it uses it to call the superclass constructor

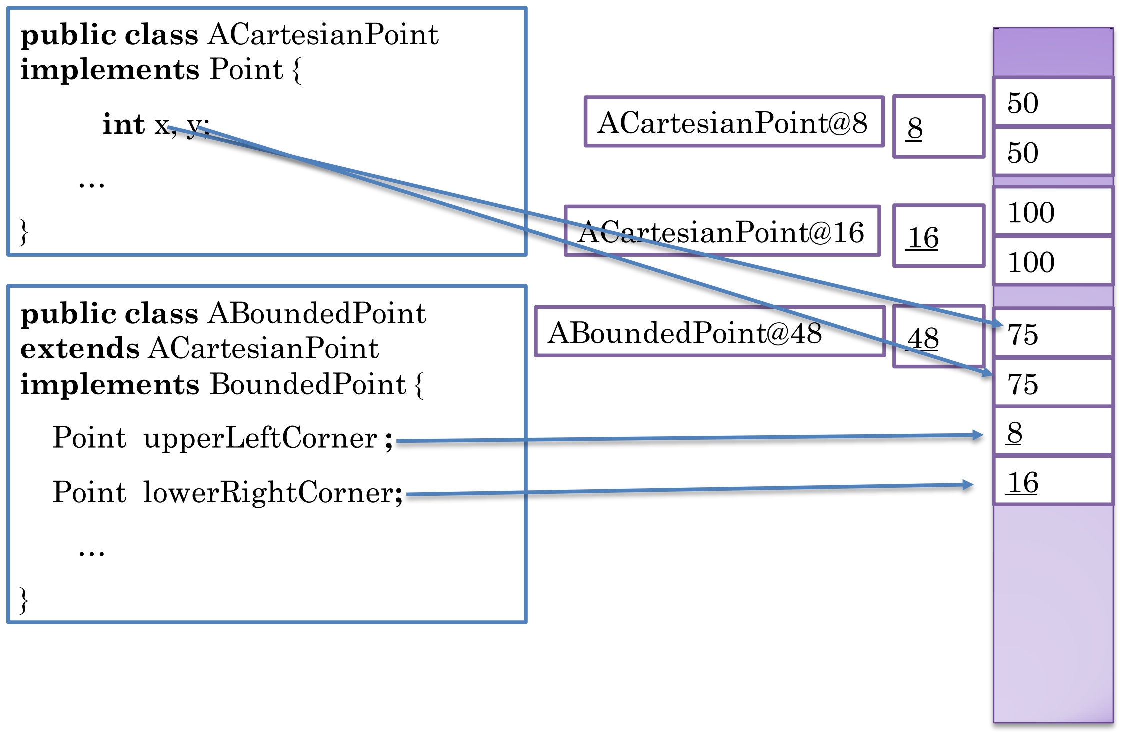
```
super(initX, initY);
```

We will use this class, together with AStringDatabase and AStringSet, to illustrate below some subtle issues with inheritance and the methods of class Object.

Inheritance and Memory Representation

One of these issues is the memory representation of instances of subclasses. Specifically, are the instance variables defined by the subclass and super classes stored in the same or different memory blocks? The following figure provides the answer. It shows the memory representation of the following instance of ABoundedPoint():

```
new ABoundedPoint(75, 75, new ACartesianPoint(50,50), new ACartesianPoint(100,100) )
```



As it shows, when an instance of a class is crated, Java allocates a single memory block for the instance variables defined by the class and all classes in its superclass chain. In this example, the block consists of the two primitive variables, x and y, defined by the super class, and the two new Object variables, upperLeftCorner and lowerRightCorner, defined by the class. Recall that each instance variable takes exactly one word and that, as the figure shows, a primitive variable directly stores a value while an object variable stores a memory address or pointer. In this figure, pointers are underlined. As it shows, the upperLeftCorner contains the address 8, which points to an instance of ACartesianPoint, which in turn, is a memory block containing two int variables defining the x and y coordinates.

By storing all variables of an object, Java makes it simpler to allocate, copy, access and free up the memory associated with these variables.

toString()

To better understand inheritance and Object, the last class in the superclass chain of all classes, let us try and understand in more depth and override the three methods of it identified above: toString(), equals(), and clone().

Let us begin by overriding in `AStringSet` the `toString()` method inherited from class Object:

```
public String toString() {
      String retVal = "";
      for (int i = 0; i < size; i++)
            retVal += ":" + contents[i];
      return retVal;
```

```
    }
```

The method returns a ":" separated list of the elements of the collection:

```
stringSet.toString() → "James Dean:John Smith"
```

Recall that the implementation inherited from Object gives us the class name followed by the memory address:

```
stringSet.toString() → "AStringSet@1eed58"
```

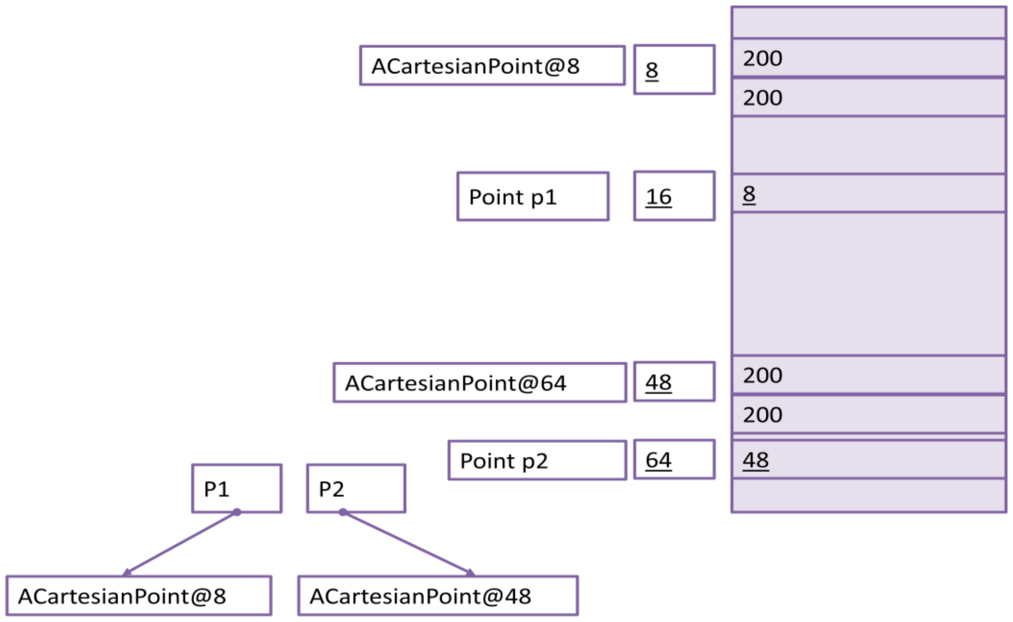
Many classes override the `toString` method, since the default implementation of it inherited from `Object` is not very informative, returning, as we saw before, the class name followed by the object address. Recall also that `println` calls this method on an object when displaying it. The reason why `println` tends to display a reasonable string for most of the existing Java classes is that these classes have overridden the default implementation inherited from Object.

equals()

Java already provides an operator to check for equality, ==, so why do we need a method that, based on its name, seems to do the same thing? To illustrate the difference between == and equals(), consider the following statements:

```
Point p1 = new ACartesianPoint(200, 200);
System.out.println(p1 == p2);
p1 = new  ACartesianPoint (200, 200);
System.out.println(p1 == p2);
```

The == operator dereferences the two pointers, and compares the resulting objects. When the first statement is executed, both p1 and p2 refer to the same object. Therefore, we can expect the first print statement to print "true". But what about the second print statement? Both variables refer to the same logical point in the coordinate space, the point with the coordinates (200,200). However, they refer to different physical objects, as shown below.

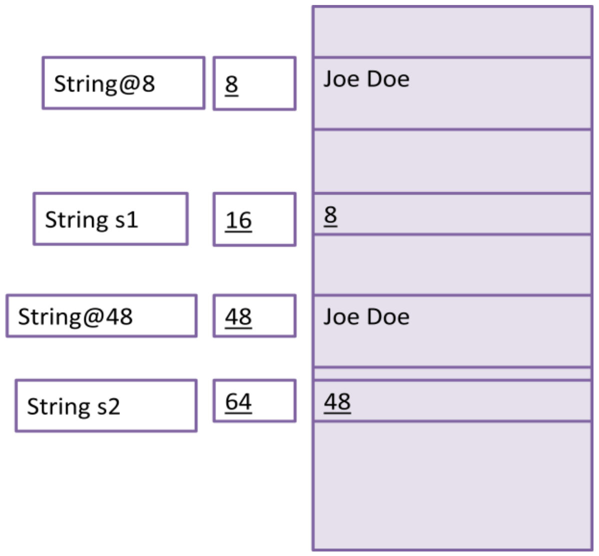


The == operator, in fact, simply checks if its left and right hand side are the same physical object. If not, it returns the false value. It does not understand the concept of two physical objects being the same logical entity. It is the responsibility of each object to define a method that checks if two objects represent the same logical entity. The convention is to call this method, `equals()`. Several predefined classes such as `String` provide such a method.

In String, this method does a character-by-character comparison of the strings that are compared, and returns true if the two strings have the same sequence of characters. The following interaction shows the difference between == and `equals()` for strings:

```
String s1 = “hello world”;
String s2 = “hello world”;
System.out.println(s1==s2);
System.out.println(s1.equals(s2));
s1 = s2;
System.out.println(s1==s2);
System.out.println(s1.equals(s2));
```

All print statements except the first one will print “true”. The reason why the first one returns false is that the two strings are stored in separate memory blocks, as shown in the figure below.



Consider now the following code:

```
            Point p1 = new ACartesianPoint(200, 200);
            p1 = new  ACartesianPoint (200, 200);
            System.out.println(p1.equals( p2));

            StringHistory stringHistory1 = new AStringHistory();
            StringHistory  stringHistory2  = new AStringHistory();
            stringHistory1.equals(stringHistory2);
```

Both println() calls print **false**. In other words, the equals() method, in these two cases, has the same behavior as ==. The reason is that we have not redefined equals() for instances of StringHistory and Point and the default behavior of equals() is the same as ==:

```
//implementation in Object
public boolean equals(Object otherObject) {
            return this == otherObject;
}
```

Each class that declares instance variables whose values influence equality must redefine equals(). To illustrate, suppose users of AStringSet are not happy with the default behavior of equals(). We can add to the class the following to override the default implementation:

```
public boolean equals(Object otherObject) {
      if (otherObject == null || !(otherObject instanceof  AStringHistory))
            return false;
       AStringHistory  otherStringHistory = (AStringHistory) otherObject;
       if (size != otherStringHistory.size)
            return false;
       for (int index  = 0; index < size; index++)
            if (!contents[index].equals(otherStringHistory.contents[index]))
                        return false;
       return true;
}
```

The operation o **instanceof** T returns true if the class of o IS-A T. This operation is used to return false when the other object is not a string history. The value of null IS-A T, for all T. Since **null** IS-A StringHistory, an extra check is needed to determine if the otherObject is **null**. If the other object is a non null StringHistory, the method does an element-by-element comparison of the two collections to determine if they are equal. To do so, it accesses the `contents` and `size` variables of the two instances that are compared. These variables are actually defined in the superclass AStringHistory. In fact, AStringDatabase and AStringSet do not define any instance variables. Thus, it is better to move the method to AStringHistory, thereby allowing all instances of AStringHistory and its subtypes to use it.

Accessing arbitrary variables/methods of remote instances

The implementation above illustrates a feature of Java we have not seen before. When a method is called on an instance I of class C, it is possible not only to access arbitrary variables and methods of I but also all other instances of class C. As we saw earlier, to access instances of I, we either omit the target instance:

```
        contents[index];
```

or use the keyword **this** to identify it:

```
        this. contents[index];
```

To access the variables of some other instance of the class, which we will refer to as a remote instance, we replace this with some variable holding a pointer to the instance. In the example above, otherStringHistory holds a pointer to the remote instance. Hence we use this variable to indicate the target object:

```
        otherStringHistory.contents[index];
```

We can use the same syntax to refer to arbitrary methods of the remote instance. In general, in a class definition, all methods and variables of all instances of the class are visible.

Accessing public vs. arbitrary members of remote instances

In the example above, we broke an important rule given before by using a class to type a variable:

```
        AStringHistory  otherStringHistory = (AStringHistory) otherObject;
```

Had we used the interface of the class to type it

```
        StringHistory otherStringHistory = (StringHistory) otherObject;
```

we would not have been able to access non public members (methods/variables) of the remote instance as these are not defined by interface. Sometimes in a class, it is necessary to access internal members of remote instances. In that case, we are forced to use it for typing. However, in this example, the interfaces exposes the required information, as illustrated by the following rewrite of equals:

```
public boolean equals(Object otherObject) {
    if (otherObject == null ||!(otherObject instanceof  StringHistory))
        return false;
    StringHistory  otherStringHistory = (StringHistory) otherObject;
    if (size != otherStringHistory.size())
        return false;
    for (int index  = 0; index < size; index++)
        if (!contents[index].equals(otherStringHistory.elementAt(index)))
                return false;
    return true;
}
```

This implementation is more polymorphic in that it allows us to compare arbitrary implementations of StringHistory and not only those that are instances of AStringHistory. It is slightly less efficient because the variables of the remote instance are access indirectly, through public methods, rather than directly. In most applications, this inefficiency is not a problem.

Overriding vs. Overloading

An even more elegant implementation of equals() is given below:

```
public boolean equals(StringHistory  otherStringHistory) {
     if (otherStringHistory == null || size != otherStringHistory.size())
        return false;
    for (int index  = 0; index < size; index++)
        if (!contents[index].equals(otherStringHistory.elementAt(index)))
                return false;
    return true;
}
```

This implementation does not have use the **instanceof** operation, which makes the code messy. However, this implementation does not really override the equals() method inherited from Object as its parameter type is different. Hence it overloads rather than overrides the inherited method. As a result, the method does not hide the inherited method; both methods are available for invocation. If we wish to invoke the overloaded method on instances of StringHistory, we must add the signature (header) of the method to the interface. Once we do that, the syntax for invoking it is exactly the same as the one for the inherited method:

```
StringHistory stringHistory1 = new AStringHistory();
StringHistory  stringHistory2  = new AStringHistory();
stringHistory1.equals(stringHistory2);
```

The equals that accepts the more specific argument type, StringHistory, is called, even though the equals() in objects would also be legal.

On the other hand, the call:

```
stringHistory1.equals("Not an instance of StringHistory");
```

would call the equals() in Object.

It seems that overloading and overriding in this example give the same results. If the argument is an instance of StringHistory, then it seems the more specialized equals() is called. Otherwise, in the overriding case, the specialized method is called, which returns false, and in the overloaded case, the more general method is called, which also return false.

However, they can indeed give different results. The reason is that what matters, when overload resolution is done, is not the type of the actual object assigned to a variable but the type of the variable. The reason is that overload resolution is done at compile time, and at this time, it is not possible to determine the exact type of the objects that will be assigned to it. Thus if we type the second instance of StringHistory as Object:

```
StringHistory stringHistory1 = new AStringHistory();
Object stringHistory2 = new AStringHistory();
stringHistory1.equals(stringHistory2);
```

then the more general equals()will be called and the result will be false. Even if we use StringHistory to type both variables, we can use a cast to call the equals() defined in Object:

```
StringHistory stringHistory1 = new AStringHistory();
StringHistory stringHistory2 = new AStringHistory();
stringHistory1.equals((Object)stringHistory2);
```

Overloading and IS-A

As we saw above, the is-a relation is used in overload resolution: if a call matches multiple overloaded methods, then the one that declared more specific formal arguments is used. In the example above, the formal argument of the equals() in AStringHistory is StringHistory, which is more specific than StringHistory.

To better understand the relationship between overloading and IS-A, let us consider some more examples.

Suppose, we define in AStringSet an overriding equals method with the following signature:

```
public boolean equals (Object otherObject);
```

and defined in AStringHistory an overloaded equals method with the following signature:

```
public boolean equals (StringHistory otherObject);
```

and executed the following code:

```
StringSet stringSet1 = new AStringSet();
StringSet stringSet2 = new AStringSet();
stringSet1.equals(stringSet);
```

It may seem a bit ambiguous as to which equals() is called in the third statement. The overriding one in AStringSet is in the more specific class, while the overloaded one in AStringHistory has the more specific argument. The one is the more specific class, however, is a different method, even though it has the same name. Therefore, Java will choose the method with the more specific argument types, regardless of which class it is defined in.

As another example, let us consider the following two variations of equals, which could be defined in arbitrary classes:

```
public boolean equals (StringHistory stringHistory1,
                Object stringHistory2) {
        …
}
public boolean equals (Object stringHistory1,
                StringHistory stringHistory2) {
        …
}
```

In these implementations, the two instances that are to be compared are both passed as arguments. Hence it does not matter on what objects these methods are actually called (which means they should really be static methods).

Now suppose we make the call:

```
equals(new AStringSet(), new AStringSet());
```

Both overloaded methods can accept the two arguments – which one should be called? Neither class has formal parameters that are of more specific types. Thus, the correct call is ambiguous, and Java will say so at compile time. We can, of course, use casts to disambiguate:

```
equals(new AStringSet(),  (Object) new AStringSet());
```

In this case the first equals() is called.

If we add a third equals method:

```
public boolean equals (StringHistory stringHistory1,
                StringHistory stringHistory2) {
        …
}
```

Then the call:

```
equals(new AStringSet(), new AStringSet());
```

invokes this new overloaded method as each of its formal parameters is more specific than the corresponding formal parameter of the two other methods. Thus, interesting, adding an overloaded method reduces rather than increases the ambiguity of overload resolution!

Given these three definitions of equals, which one is invoked by the following call?

```
        equals(null, null);
```

null can be typed as any object type, so it may seems that the call is still ambiguous. However, as the types of the formal parameters of the third equals () are most specific, there is really no ambiguity, and this method is called.

Suppose we add a fourth equals(), one that takes Point arguments:

```
public boolean equals (Point point1, Point point2) {
        …
}
```

Now the call:

```
        equals(null, null);
```

is indeed ambiguous as none of the matching equals() declared more specific types. We can resolve the ambiguity by explicitly casting null:

```
        equals ((StringHistory)null, (StringHistory) null);
```

Annotations and Making Override Explicit

As overloaded and overriding can lead to different results, it is important to not accidentally overload when we intended to override, and vice versa. To prevent such mistakes, Java supports override annotations illustrated below:

```
@Override
public boolean equals(Object otherObject) { … }
```

Annotation is a typed “comment” about a method, class, or package that can be processed by some tool such as compiler, Eclipse or ObjectEditor at compile/execution time. It starts with the character, @, as illustrated below. Java supports several types of annotations. The override annotation type is associated with a method and tells Java that the method overrides an existing method. If the method does not in fact do so, the compiler will give an error. In the above example, since the method signature matches that of the equals() method of Object, no error will be given. Similarly, the following annotated method definition in AStringSet will give no error:

```
@Override
public void addElement(String element) { … }
```

On the other hand, the following method declaration in AStringHistory will give an error as it overloads rather than overrides the Object equals() method:

```
@Override
public boolean equals(StringHistory otherStringHistory) { … }
```

Interestingly, the following annotated method declaration in AStringHistory does not give an error:

```
  @Override
  public String elementAt (int index) {  return contents[index]; }
```

Recall that AStringHistory is a direct subclass of Object, which does not define an elementAt() method. In the definition of the override annotation, Java does not distinguish between IS-A and inheritance. An override annotation for method M in class C indicates that M is a(n) (re)implementation of some M declared in some type T, where C IS-A T. In other words, Java considers the implementation of an interface method also as overriding. This is inconsistent will all definitions of overriding in the literature.

Java allows programmers to define their own annotation types to be processed by tools written by them. This extensibility is used in the design of ObjectEditor. For example, the following annotated interface declaration tells ObjectEditor to not consider the interface as an atomic shape type even though it follows all the rules of a point type by having **int** X and Y properties and including the substring Point in its name:

```
public interface NotAPoint {
        int getX();
        int getY();
        …
}
```

As the declaration shows, an annotation can take arguments. In Java, an annotation is actually represented by an interface or class. The arguments to the annotation are passed to a special method defined by the interface or class.

Shallow Copy

Let us finish our exploration of the class Object by looking finally at the method clone(). To motivate it, let us return to the Point example.

```
        p1 = new ACartesianPoint(200, 200);
        p2 = p1;
        p1.setX (100);
        System.out.println(p2.getX() == p1.getX());
```

As we saw before, the code above will print **true**. The reason is that assignment simply copies pointers. What if did not want p1 and p2 to share the same object? Instead, we wanted the initial value of *p2*to be a *copy* of the object referenced by *p1;* and later wanted to change the copy without affecting the original object? We might want to do so because we want a backup of *p1* to which we would like to revert later.

Since assignment does not do the job for us, we can extract the information in ACartesianPoint and use this to create a new instance with the same state:

```
p1 = new ACartesianPoint(200, 200);
p2 = new ACartesianPoint (p1.getX(), p1.getY());
p1.setX (100);
System.out.println(p2.getX() == p1.getX());
```

This time the output will be false. However, this approach requires the copier to do the copying, which may not seem much work in this case, but would be more if the object to be copied had several instance variables. Therefore, a better approach is to make the copied object do the work of copying. That is, the copier should simply invoke a method on the object to be copied that returns a copy. The clone() method in Object is such a method. As its name indicates, it returns a copy of the object on which it is invoked. Since the method can be invoked on an object of any type, its return type is Object:

```
// defined in Object
public Object clone() { … }
```

This return type can be cast to the actual type, as shown below:

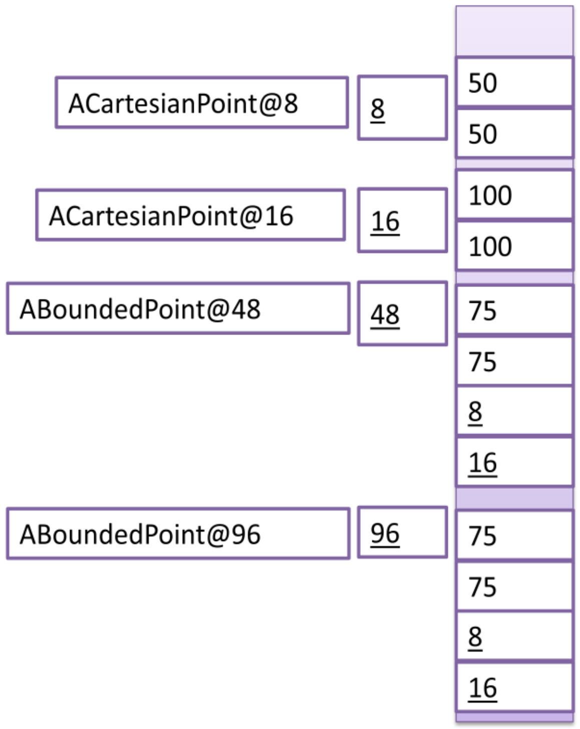
```
p1 = new ACartesianPoint(200, 200);
p2 = (Point) p1.clone();
p1.setX (100);
System.out.println(p2.getX() == p1.getX());
```

Again, the output is false, as clone() creates a new copy with separate instance variables.

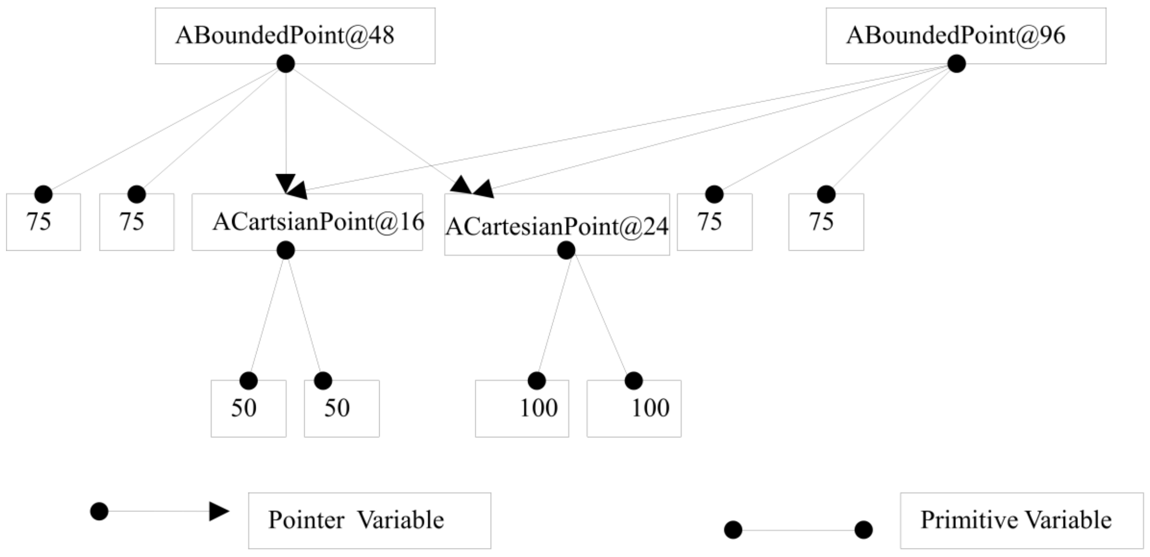
To better understand the notion of copying, let us consider instances of a more complicated type. Consider the following code:

```
 p1 = new ABoundedPoint(75, 75,  new ACartesianPoint(50,50), new ACartesianPoint(100,100) );
p2 = (BoundedPoint) p1.clone();
p1.setX (100);
p1.getUpperLeftCorner().setX(200);
System.out.println(p2.getX() == p1.getX());
System.out.println (p1.getUpperLeftCorner().getX() == p2.getUpperLeftCorner().getX() );
```

The first output will print false but the second one will, in fact, print true. The reason is that Object implements clone() by simply making a copy of the memory block of the copied object, as shown in the figure below:



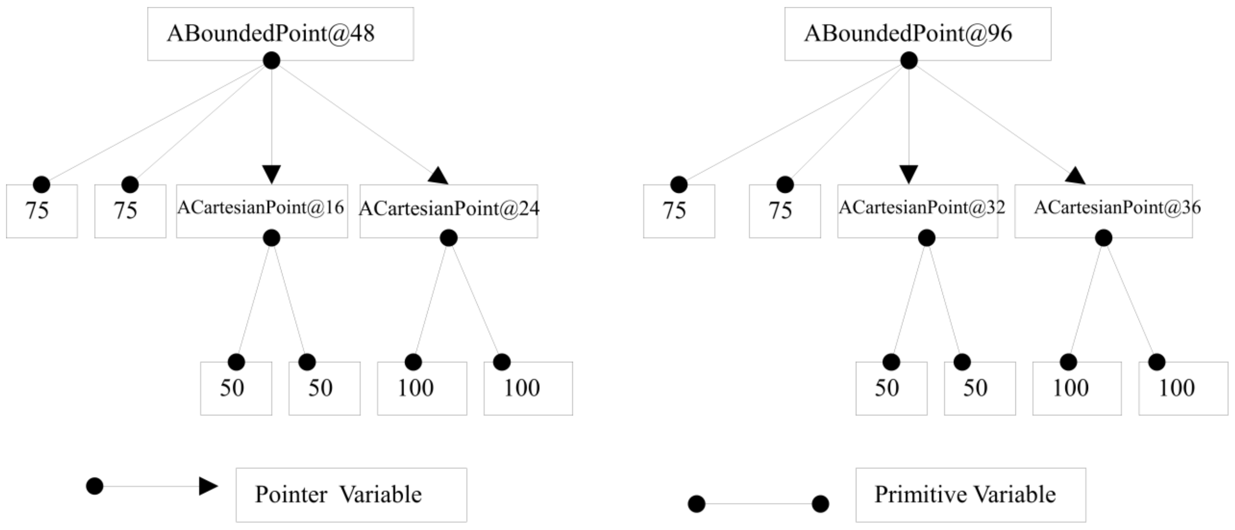
Here, the clone() method, when executed on the object, ABoundedPoint@48, creates a new object, ABoundedPoint@48, whose memory block is a copy of the memory block of the first object. The two primitive instance variables, x and y, of the new copy are assigned copies of the values of the x and y variables of the original object. The two pointer variables in the copy, however are the assigned copies of the *pointers* to the (Point) objects referenced by the upperLeftCorner and lowerRightCorner of the original object. These subobjects of the original object are not themselves copied. This means that object variables in the copy point to the same objects as the corresponding variables in the original object. The second println() call returns true as p1.getUpperLeftCorner() and p2. getUpperLeftCorner() refer to the same object, ACartesianPoint@8. This is shown graphically in the figure below:



Each line in the picture represents an instance variable of the object. A copy that simply duplicates the memory block of the copied object is called a *shallow copy*. The word shallow indicates that it copies only the top level of the physical structure of the object.

Deep Copy

A copy that also copies memory blocks of components of the copied object is called a *deep copy.* The following figure illustrates deep copy of our example object:



Such a copy is not provided by Java, so we must override the clone() method to implement it:

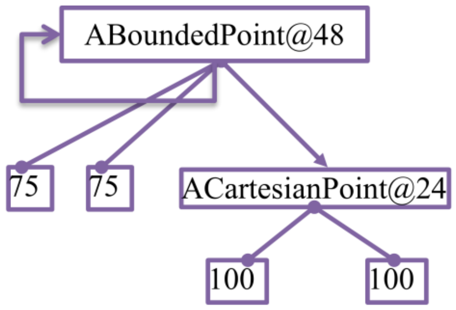
```
public Object clone() {
        return new ABoundedPoint (x, y, (Point) upperLeftCorner.clone(),
                                                (Point) lowerRightCorner.clone());
};
```

Here we construct a new instance of ABoundedPoint that has a copy of the objects to which the upperLeftCorner and lowerRightCorner instance variables point.

This copy, however, does not always work. The problem is illustrated by the example below:

```
p1 = new ABoundedPoint(75, 75,  new ACartesianPoint(50,50),  new ACartesianPoint(100,100) );
p1.setUpperLeftCorner(p1);
p2 = (BoundedPoint) p1.clone();
```

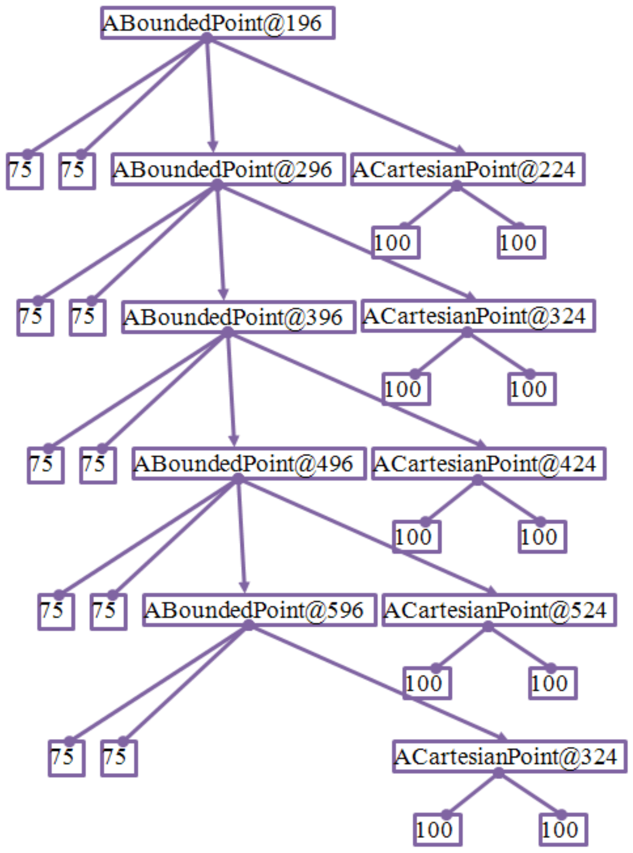
Here, we have created a recursive structure, that is, a structure in which a child component points to its ancestor:



As a result, when the clone method is invoked on this object, the following call leads to an infinite recursion:

```
(Point) upperLeftCorner.clone()
```

Each time the call is made, a new copy of ABoundedPoint@48 is made, and the call is made again, which makes another copy of the object, and so on, leading to the creation of an infinite number of copies of the object, some of which are shown below:



Thus, we must be careful in either how we implement deep copy or the kind of objects on which we try to invoke this operation. Recursive structures cannot be banned as they are very useful. A class of problems called graph problems require such structures.

The Java Object class avoids this problem in its implementation of clone() by providing a shallow copy.

Supporting Multiple Copy Operations

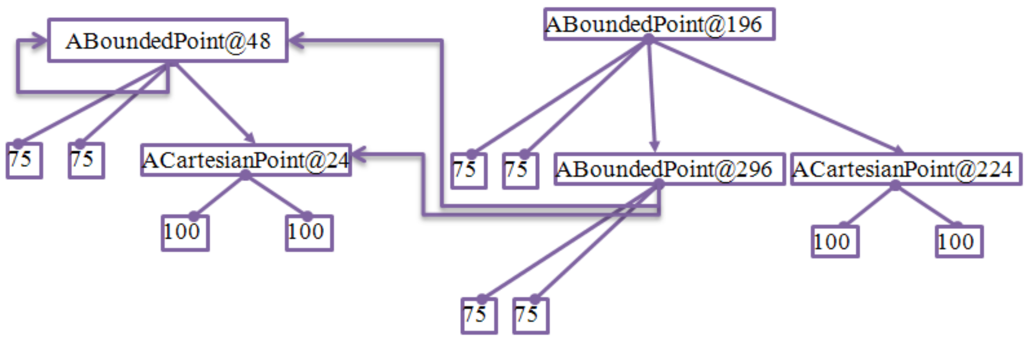
One way to reduce the problem of copying recursive structures is to associate each object with *both* a shallow and deep copy, and allow the deep copy to determine if shallow or deep copies of components are made. This solution is illustrated below for our example class, *ABoundedPoint*:

```
public Object shallowCopy() {
        return new ABoundedPoint (x, y, upperLeftCorner, lowerRightCorner);
};

public Object deepCopy() {
        return new ABoundedPoint (x, y, (Point) upperLeftCorner.shallowCopy(),
                                        (Point) lowerRightCorner.shallowCopy());
};
```

The “deep” copy in this solution is not a full deep copy as it does not copy all levels in the physical structure of the copied object – it is simply a deeper copy than a shallow copy. However, a call to it will never lead to infinite recursion.

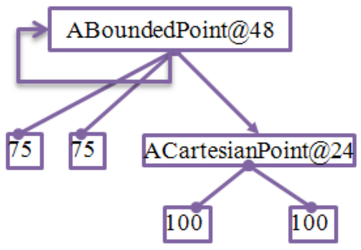
An extension of the approach of providing both a shallow and deep(er) copy is taken in Smalltalk. Each Smalltalk object provides three copy methods: shallow, deep, and regular copy. The shallow copy is like the Object clone() method: It creates a new object and assigns instance variables of the copied object to corresponding instance variables of new object. The deep copy creates a new object and assigns a *regular copy* of each instance variable of the copied object to corresponding instance variable of new object. The semantics of the regular copy of an object of some class C is defined by that class. It is expected to either be a shallow or deep copy – the programmer of each class defines which of these two choices is taken. By default, the regular copy is a shallow copy. In our cyclic example, if the regular copy is a shallow copy, then a deep copy of the cyclic structure on the left would result in the structure on the right:

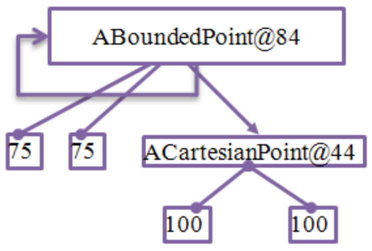


Here the deep copy creates a new instance of ABoundedPoint (ABoundedPoint@196), and then does a copy of the two object pointers in it. As this copy is a shallow copy, we get new instance of ABoundedPoint (ABoundedPoint@296) and a new instance of ACartesianPoint (ACartesianPOint@224) whose memory content are copies of the objects representing the upper left corner and lower right corner of the original object. This results in the two object pointers in ABoundedPoint@296 pointing back to the original object.

Detecting Recursion

The multiple copy solution does not, of course, work when a full deep copy is needed. In this situation, recursive structures can be handled by detecting recursion while performing the copy operation, that is, before copying a component, detecting if the component has already been copied in the operation. When recursion is detected, we can either not copy the component, or give an error, or create an identical or isomorphic structure. In the example above, we could create an isomorphic structure y creating another instance of a BoundedPoint whose upper left corner points to it, as shown below.





While the Java clone method supports shallow copy, called serialization, which makes object copies that are written to files or sent across the network, supports such isomorphic copies.

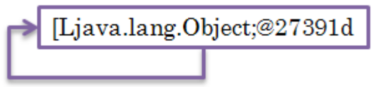
Why no Recursive Print?

The fact that recursive structures can be created is probably the reason that Java println() does not print the elements of arrays, instead simply displaying the id of the array and the type of the elements of the array:

```
[Ljava.lang.Object;@27391d
```

It is possible to use an array to create a recursive structure:

```
Object[] recursive = new Object[1];
recursive[0] = recursive;
```



A println() that recursively printed each element of a recursive array such as the one above would recurse forever.

ObjectEditor faces a similar problem when creating a widget structure for the logical structure of an object. The current version detects recursion and does not create a widget for a component for which it has already created a widget earlier.

Other Object Methods

The discussion above helps us better understand three operations provided by class Object: toString(), equals(), and clone(). This class provides several other methods:

- hashCode():This is relevant to hashtables, which you will learn in depth in data structures. Think of a hashCode as the internal address of object.
- Various versions of wait() and notify():These are relevant to threads – you will study them in depth in an operating systems course.

- getClass(): This method returns the class of an object, on which one can invoke “reflection” methods, which are beyond the scope of most undergrad courses. These methods allow one to determine and invoke the methods of a class. ObjectEditor uses these methods.
- Finalize(): This method is called when the object is garbage collected, discussed below.

Objects and Interfaces

As we have seen above, it is possible to invoke an Object method on any object variable. If the variable is typed by a class, this makes sense, as it is possible to invoke any method declared in the class or its super class chain; and Object is the last type in any superclass chain. However, if the variable is typed by an interface, this rule does not make sense, as Object is a class and not an interface, and thus cannot be on the supertype chain of any interface. Yet, if we type a variable by an interface:

```
StringHistory stringHistory1, stringHistory2;
```

we can indeed call Object methods on that variable:

```
stringHistory1.equals(stringHistory2);
```

The reason this is legal is that Java uses a special rule to allow all interfaces to “inherit” Object methods. The cleaner solution would have been to associate Object with an interface, and make this interface the last interface in the super type chain of all interfaces. Unfortunately, the designers of the language and libraries have had a schizophrenic attitude towards interfaces, using them in some situation and not in others. Had they followed our rule of making every class implement one or more interfaces, we would not have this fundamental problem with Object methods.

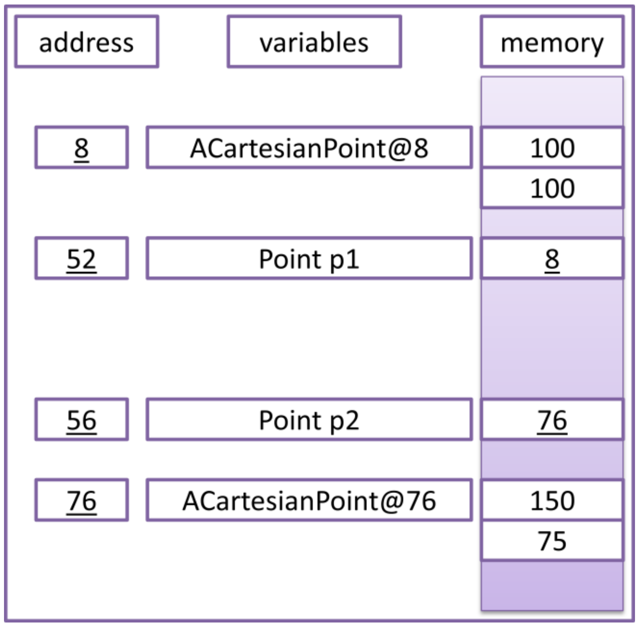
Garbage Collection

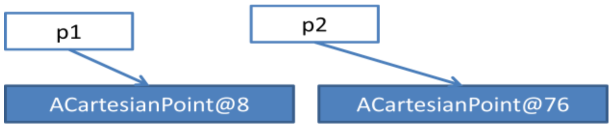
Suppose we execute the following code:

```
Point p1   = new  ACartesianPoint(100,100);

Point p2   = new  ACartesianPoint(150,75);
```

Two new variables are created, which point to different objects, as shown in the figures below:

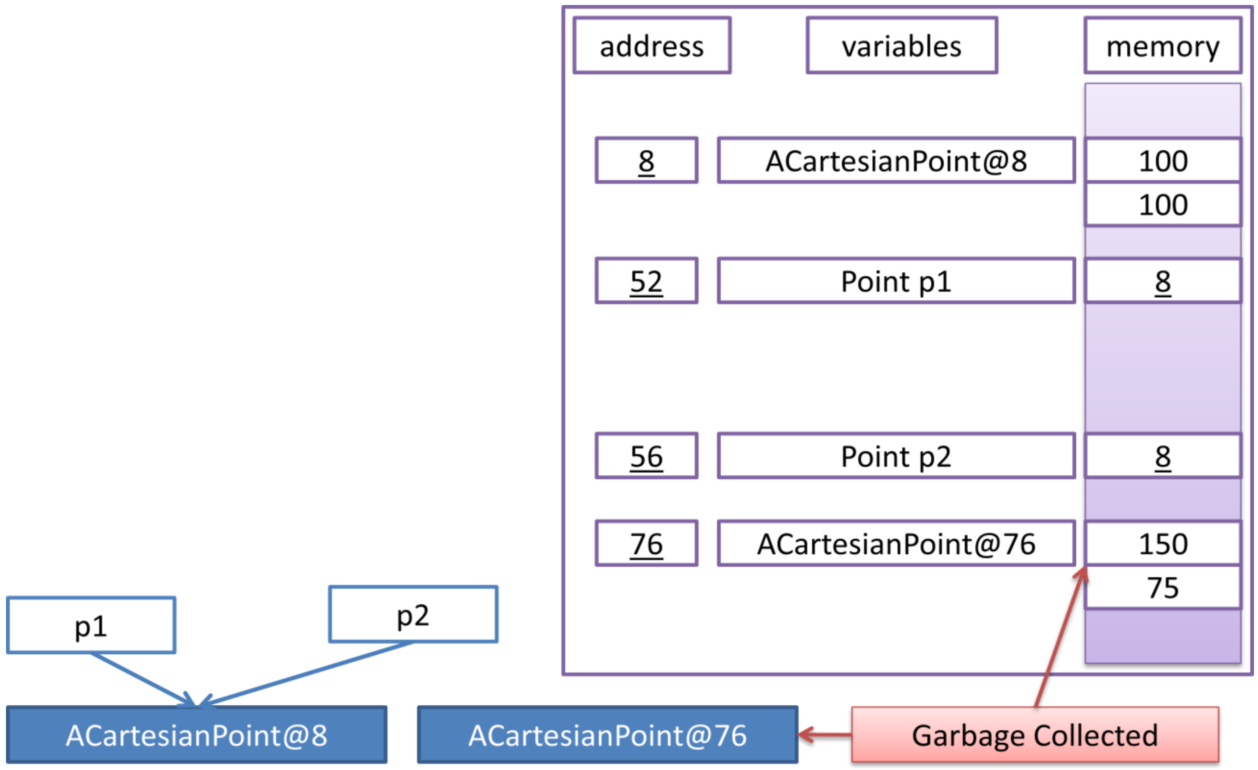




What if we now execute the following code:

p2 = p1;

Now both variables point to the same object, and the object to which p2 pointed cannot ever be accessed. This is shown below:

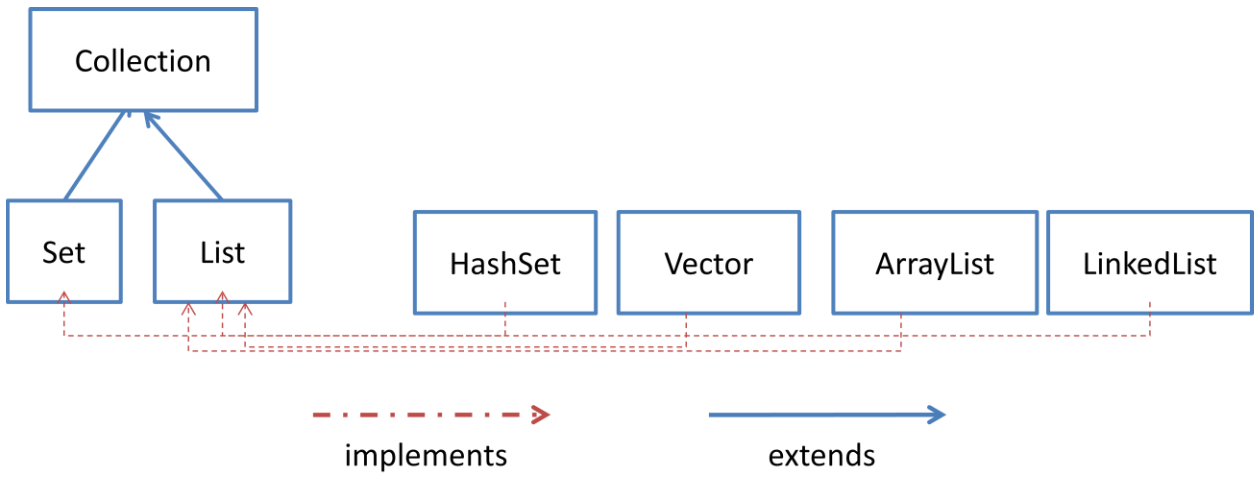


As no variable refers to the object, it is *garbage collected.* With each object, Java keeps a count, called a *reference count*, that tracks how many object variables store pointers to it. When this count goes to zero, it collects the object as garbage, since no other variable will ever be able to point to it again.

Automatic garbage collection is a really nice feature of Java since in most traditional languages such as C, the programmer is responsible for deleting objects. In such languages, the danger is that we may accidentally delete something that is being used, thereby creating *dangling pointers* to it, or forget to delete something that is not being used, thereby creating a *memory leak* that keeps wasting memory. On the other hand, garbage collection makes Java slower, since Java must interrupt our program execution to do garbage collection.

Collection Inheritance in Java

In this chapter, we have seen how inheritance can be used while defining collection classes. The Java API also addresses this issue. The hierarchy it creates has some similarity with the one we created. Part of the hierarchy is given below:



It defines two interfaces, Set and List, which are both subtypes of Collection. This is analogous to StringDatabase and StringSet being subtypes of StringHistory. Vector, ArrayList, and LinkedList provide three different implements of the List interface. In earlier versions, Vector did not implement any interface. When Java programmers felt the need for additional implementations with the same functionality, they created the List interface. Both Vector and ArrayList use arrays to create a variable-sized collection – the main difference is in how they grow when new elements are added. LinkedList uses a different data structure, called a linked list, which you will study later. Similarly, there are a variety of classes that implement the Set interface, we see only HashSet in this figure.

Summary

- Java allows classes and interfaces to inherit declarations in existing classes and methods, adding only the definitions needed to extend the latter.
- An inherited method can be overridden by a new method.
- Inheritance and implementation are examples of IS-A relationships.
- If T2 IS-A T1, then a value of type T2 can be assigned to a variable of type T1.
- All variables of an object, including its inherited variables, are stored in a single memory block.
- Overriding != overloading
- If two overloaded method match a call, the one with more specific parameter types is chosen.
- Casts may be needed to disambiguate between overloaded methods.
- equals() != ==
- Copies can be shallow or deep depending on whether components of the copied object are themselves copied or not.
- Recursive structures interfere with deep copy.
- Unreferenced objects are garbage collected.

Exercises