Generics

Object Oriented Programming

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1

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2

Motivation

- Often the same operations have to be performed on objects of unrelated classes
  - A typical solution is to use **`Object`** references to accommodate objects of any type
- **`Object`** references bring cumbersome code
  - Several explicit casts are required
  - Compile-time checks are limited
  - Down-casts can be checked at run-time only
- Solution
  - Use **generic** classes and methods

Example

- We may need to represent pairs or values different types (e.g. **`int`**, **`String`**, etc.)
- Use of **`Object`** to allow any type

```
public class Pair {
  Object a, b;
  public Pair(Object a, Object b )
  {  this.a=a; this.b=b; }
  Object first(){ return a; }
  Object second(){ return b; }
}
```

Note: No primitive types, only wrappers allowed

Example: Object-based use

- **`Object`** allows usage with diverse types

```
Pair sp = new Pair("One", "Two");
Pair ip = new Pair(1,2);
```

- Though you need explicit down-casts:

```
String a = (String) sp.second();
int i = (Integer) ip.first();
```

- Down-casts are checked at run-time

```
String b = (String) ip.second();
```

`ClassCastException` at run-time

Example: Object-based use

- No check is possible at compile time about homogeneity of elements:

```
Pair mixpair = new Pair(1,"Two");
Pair pairmix = new Pair("One”,2);
```

- Extra code is required for safety:

```
Object o = mixpair.second();
if(o instanceof Integer){
  i = (Integer)o;
}else { … }
```

Generic class

```
public class Pair<T> {
  T a, b;
  public Pair(T a, T b) {
    this.a = a;  this.b = b;
  }
  public T first(){ return a; }
  public T second(){ return b; }
  public void set1st(T x){ a = x; }
  public void set2nd(T x){ b = x; }
}
```


Generics use

- Declaration is slightly longer:

```
Pair<String> sp = new Pair<>("One","Two");
Pair<Integer> ip = new Pair<>(1,2);
Pair<String> mixp = new Pair<>(1, "Two");
```

Compiler error

- Use is more compact and safer:

```
String a = sp.second();
int b = ip.first();
String bs = ip.second();
```

No down-cast is required

Integer can be auto-unboxed

Compiler error: type mismatch

Generic type declaration

- Syntax:

(**class**|**interface**) ***Name*** <$\mathbf{P}_1$ {,$\mathbf{P}_2$}>

- Type parameters, e.g. $\mathbf{P}_1$:
  - Represent classes or interfaces
  - Conventionally uppercase letter
  - Usually:
    T(ype), **R**(eturn), **E**(lement), **K**(ey), **V**(alue)

Generic Interfaces

- All standard interfaces and classes have been defined as generics
  - since Java 5
- Use of generics leads to code that is
  - safer
  - more compact
  - easier to understand
  - equally performing

Generic **Comparable**

- Interface **java.lang.Comparable**

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

- Semantics: returns
  - a negative integer if `this` precedes `obj`
  - 0, if `this` equals `obj`
  - a positive integer if `this` succeeds `obj`

11

Generic **Comparable**

- Without generics:

```
public class Student implements Comparable{
   int id;
   public int compareTo(Object o){
      Student other = (Student)o;
      return this.id - other.id;
   }}
```

- With generics:

```
public class Student
         implements Comparable<Student> {
   int id;
   public int compareTo(Student other){
      return this.id - other.id;
   }}
```

Generic **Iterable** and **Iterator**

```
public interface List<E>{
  void add(E x);
  Iterator<E> iterator();
}
```

```
public interface Iterator<E>{
  E next();
  boolean hasNext();
}
```


Iterable example

```
class Letters implements Iterable<Character> {
  private char[] chars;
  public Letters(String s){
     chars = s.toCharArray(); }
  public Iterator<Character> iterator() {
    return new Iterator<Character>(){
      private int i=0;
      public boolean hasNext(){
        return i < chars.length;
     }
      public Character next() {
        return chars[i++];
      }
     };
} }
```

Iterable example

- Without generics

```
Letters l = new Letters("Sequence");
for(Object e : l){
  char v = ((Character)e);
  System.out.println(v);
}
```

- With generics

```
Letters l = new Letters("Sequence");
for(char ch : l){
    System.out.println(ch);
}
```


Iterable example

```
class Random implements Iterable<Integer> {
  private int[] values;
  public Random(int n, int min, int max){ … }
  public Iterator<Integer> iterator() {
    return new Iterator<Integer>(){
        private int position=0;
        public boolean hasNext() {
           return position < values.length;
        }
        public Integer next() {
           return values[position++];
        }
     };
}}
```

`Iterable` example

- Without generics:

```
Random seq = new Random(10,5,10);
for(Object e : seq){
  int v = ((Integer)e).intValue();
  System.out.println(v);
}
```

- With generics:

```
Random seq = new Random(10,5,10);
for(int v : seq){
  System.out.println(v);
}
```


Diamond operator

- Reference type parameter must match the class parameter used in instantiation
  - E.g.

```
List<String> l=new LinkedList<String>();
```

- The Java compiler can infer the type when the diamond operator is used:

```
List<String> l = new LinkedList<>();
```

  - Since Java 7

Generic method

- Syntax:

  modifiers **<T>** ***type*** **name(pars)**

- pars can be:
  - as usual
  - **T**
  - **type<T>**

19

Generic Method Example

element must have same type as array type

```
public static <T>
  boolean contains(T[] ary, T element){
    for(T current : ary){
      if(current.equals(element))
        return true;
    }
    return false;
 }
```

```
String[] words = { … };
boolean found = contains(words,"fox");
```

20

Unbounded type

- The type parameters used in generics are unbounded by default
  - I.e. there are no constraints on the types that can be substituted to the type parameters
- The safe assumption for any type parameter **`T`** is that **`T extends Object`**
  - References of a type parameter **`T`** at least provide members that are defined in class **`Object`** (e.g., **`equals()`**)

Unbounded generic sorting

```
public static <T>
void sort(T v[]){
  for(int i=1; i<v.length; ++i)
    for(int j=1; j<v.length; ++j){
      if(v[j-1].compareTo(v[j])>0){
        T o=v[j];
        v[j]=v[j-1];
        v[j-1]=o;
  } }
}
```

method **`compareTo(T)`** is undefined for type T

Bounded types

- Express constraints on type parameters

```
< T extends B >
```

- class **T** can be replaced only with types extending **B** including **B** itself
  - **B** is called an upper bound
- It is possible to specify multiple upper bounds

```
<T extends B1 { & B2 } >
```


Bounded generic sorting

```
public static <T extends Comparable>
void sort(T v[]){
  for(int i=1; i<v.length; ++i)
    for(int j=1; j<v.length; ++j){
      if(v[j-1].compareTo(v[j])>0){
        T o=v[j];
        v[j]=v[j-1];
        v[j-1]=o;
  } }
}
```

Ok: method **compareTo(T)** is defined in **Comparable**

Bounded generic sorting

Since Comparable is a generic interface itself

```
public static <T extends Comparable<T>>
void sort(T v[]){
  for(int i=1; i<v.length; ++i)
    for(int j=1; j<v.length; ++j){
      if(v[j-1].compareTo(v[j])>0){
        T o=v[j];
        v[j]=v[j-1];
         v[j-1]=o;
} } }
```


Bounded `Comparator`

```
public static <T,C extends Comparator<T>>
void sort(T v[], C cmp){
   for(int i=1; i<v.length; ++i)
     for(int j=1; j<v.length; ++j){
       if(cmp.compare(v[j-1],v[j])>0){
         T o=v[j];
         v[j]=v[j-1];
          v[j-1]=o;
 } } }
```

Bounded `Comparator`

```
public static <T>
void sort(T v[], Comparator<T> cmp){
   for(int i=1; i<v.length; ++i)
     for(int j=1; j<v.length; ++j){
       if(cmp.compare(v[j-1],v[j])>0){
         T o=v[j];
         v[j]=v[j-1];
          v[j-1]=o;
 } } }
```


Java Generics

SUBTYPING AND CO-VARIANCE

Generics subtyping

- We must be careful about inheritance when generic types are involved
  - **`Integer`** is a subtype of **`Object`**
  - **`Pair<Integer>`** is NOT subtype of **`Pair<Object>`**

```
Pair<Integer> pi = new Pair<>(0,1);
Pair<Object> pn = pi;
pn.set1st("0.5");
Integer i = pi.first();
```

if this were legal then...

.. we could end up assigning a String to an Integer reference

Containers and elements

- Containers can be co-variant or invariant.
- Co-variance: elements inheritance implies containers inheritance
  - If **`A`** *extends* **`B`**
  - Then **`Container<A>`** *extends* **`Container<B>`**
  - In Java this brings to unsafe assumptions
- Invariance: elements inheritance does not imply container inheritance
  - Type safe assumption

Generics invariance

- Generics types are invariant
- The elements type are the type arguments
  - The fact **Integer** extends **Object** does not imply **Pair<Integer>** extends **Pair<Object>**
- Co-variance would lead to type clashes

```
Pair<Integer> pi;
Pair<Object> pn = pi;
```

Type mismatch

Arrays co-variance

- Arrays are type co-variant containers
  - If **A** *extends* **B**
  - Then **A[]** *extends* **B[]**
- Co-variance make type clashes possible

```
String[] as = new String[10];
Object[] ao;
ao = as; // this is ok!!!
ao[1] = new Integer(1);
```

java.lang.ArrayStoreException

Invariance limitations

- An attempt to have a universal method:

```
void printPair(Pair<Object> p) {
  System.out.println(p.first()+ "-" +
                     p.second());
}
```

- Won't work with e.g. **`Pair<Integer>`**

```
  Pair<Integer> p = new Pair<>(7,4);
  printPair(p);
```

Method is not applicable for the argument

Invariance limitations

- Universal method must be generic

```
<T> void printPair(Pair<T> p) {
  System.out.println(p.first()+ "-" +
                     p.second());
}
```

- Even if declared as generic, the method in itself is not generic
  - Type T is never mentioned in the method

Wildcards

- Allow to express (lack of) constraints when *using* generic types
- `<?>`
  - unknown, unbounded
- `<? extends B>`
  - upper bound: only sub-types of B
    - Including B
- `<? super D>`
  - lower bound: only super-types of D
    - Including D

Invariance limitations

- Universal method must be generic

```
void printPair(Pair<?> p) {
  System.out.println(p.first()+ "-" +
                     p.second());
}
```

Pair of unknown

- Compiler treats unknowns conservatively

```
void clearFirst(Pair<?> p) {
  p.setFirst("");
}
```

Method is not applicable for the argument

Wildcard constraints

- The **?** (unknown) type is literally unknown therefore the compiler treats it in the safest possible way:
  - Only method from `Object` are allowed
  - Assignment to an unknown reference is illegal

Bounded wildcard – example

Cannot be invoked with `Pair<Integer>`

```
double sum(Pair<Number> p){
  return p.a.doubleValue()+p.b.doubleValue();
}
```

Defines an upper bound for the type parameter

```
<T extends Number> double sumB(Pair<T> p)
{…}
```

Unknown with upper bound
Equivalent but more compact

```
double sumUB(Pair<? extends Number> p)
{…}
```

Sorting a pair

```
void <T extends Comparable<T>>
sortPair(Pair<T> p) {
   if(p.first().compareTo(p.second()) > 0){
      T tmp = p.first();
      p.setFirst(p.second());
      p.setSecond(tmp);
   }
}
```

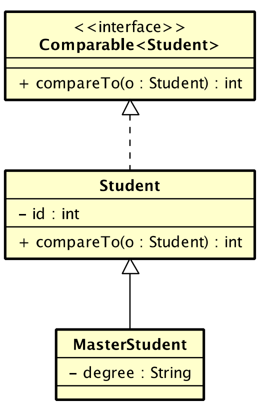

Sorting a pair example

```
Pair<MasterStudent> pm = new Pair<>(…);
sortPair(pm);
```

Method is not applicable for the argument: (Pair<MasterStudent>)

MasterStudent MasterStudent
void <~~T~~ extends Comparable<~~T~~>>
sortPair(Pair<~~T~~> p)
MasterStudent

MasterStudent does not implement Comparable<MasterStudent>



Sorting a pair

`T` must implement `Comparable` of any superclass of `T` (including `T` itself)

```
static <T extends Comparable<? super T>>
void sortPair(Pair<T> p) {
  if(p.first().compareTo(p.second()) > 0){
    T tmp = p.first();
    p.setFirst(p.second());
    p.setSecond(tmp);
  }
}
```

`MasterStudent` implements `Comparable<Student super MasterStudent>`

Sort generic

~~`T`~~ `extends Comparable<`~~`?`~~ `super` ~~`T`~~`>`

`MasterStudent` `Student` `MasterStudent`

- Why `<? super T>` instead of just `<T>` ?
  - Suppose you define
    - `MasterStudent extends Student { }`
  - Intending to inherit the Student ordering
    - Does not implement `Comparable<MasterStudent>`
    - But `MasterStudent` extends (indirectly) `Comparable<Student>`

Sort method

- On **`Comparable`** objects:

```
static <T extends Comparable<? super T>>
void sort(T[] list)
```

  - For backward compatibility, in class Array sort is defined as:
  - `public static void sort(Object[] a)`
  - No compile time check is performed.

- Using a **`Comparator`** object:

```
static <T> void
sort(T[] a, Comparator<? super T> cmp)
```


Java Generics

TYPE ERASURE

Generics classes

- The compiler generates only one class for each generic type declaration
  - Compilation erases the type parameters

```
Pair<Integer> pi = new Pair<>(1,2);
Pair<String> ps = new Pair<>("one","two");

boolean is = pi instanceof Pair;
boolean si = ps instanceof Pair;
```

Both are **`true`**

Type erasure

- Classes corresponding to generic types are generated by type erasure
- The erasure of a generic class is a raw type
  - where any reference to the parameters is substituted with the parameter erasure
  - Raw type of generic class **`G<T>`** is **`G`**
- Erasure of a parameter is the erasure of its first boundary
  - If no boundary is provided then it is **`Object`**

Type erasure – examples

- For: `<T>`
  - `T` → `Object`
- For: `<T extends Number>`
  - `T` → `Number`
- For: `<T extends Number & Comparable>`
  - `T` → `Number`

Type erasure – consequences I

- Since there is only one class, within the class no information is available about the type parameters
  - They have been erased
- The actual value of type parameter is known only to the user of a generic type
- Compiler applies checks only when a generic type is used, not within it.

Type erasure – consequences II

- Whenever a generic or a parameter is used a cast is added to its erasure
- To avoid inconsistencies and wrong expectations
  - **`instanceof`** cannot be used on generic types
  - **`instanceof`** is valid for **`G`** or **`G<?>`**

Type erasure – consequences III

- It is not possible to instantiate an object of the type parameter from within the class

```
class Triplet<T> {
  private T[] triplet;
  Triplet(T a, T b, T c){
    triplet = new T[]{a,b,c};
  }
}
```

Compiler cannot create a generic array of **`T`**

  - The erasure cannot used in any way inside the raw type

Type erasure– consequences IV

- Overloads and ovverrides are checked by compiler after type erasure

```
class Base<T> {
   void m(int x){}
        Object
   void m(T t){}
   void m(String s){}
                                             String
  <N extends String> void m(N x){}
   void m(Pair<?> l){}
}
```

Duplicate method

Type erasure– consequences V

- Inheritance together with generic types leads to several possibilities
- It is not possible to implement twice the same generic interface with different types

```
class Student implements Comparable<Student>
```

```
class MasterStudent extends Student
            implements Comparable<MasterStudent>
```

The interface **Comparable** cannot be implemented more than once with different arguments

Type inference

- Upon generic method invocation, compiler infers the type argument (capture)
- It is possible to use a type witness, although often useless
  - `Arrays.<Student>sort(sv);`
- Inference is based on
  - Target type
  - Argument type

USE OF GENERICS IN PRACTICE

Functional Interfaces

- An interface with exactly one method
- The semantics is purely functional
  - The result of the method depends solely on the arguments
  - There are no side-effects on attributes
- Can be implemented as lambda expressions
- Predefined interfaces are defined in
  - **`java.util.function`**

Standard Functional Interfaces

Interface	Method
`Function <T,R>`	`R apply(T t)`
`BiFunction <T,U,R>`	`R apply(T t, U u)`
`BinaryOperator <T>`	`T apply(T t, T u)`
`UnaryOperator <T>`	`T apply(T t)`
`Predicate <T>`	`boolean test(T t)`
`Consumer <T>`	`void accept(T t)`
`BiConsumer <T,U>`	`void accept(T t, U u)`
`Supplier <T>`	`T get()`

Primitive specializations

- Functional interfaces handle references
- Specialized versions are defined for primitive types (**`int`**, **`long`**, **`double`**, **`boolean`**)
- Functions: `To`*`Type`*`Function`
  `Type1``To`*`Type2`*`Function`
- Suppliers: *`Type`*`Supplier`
- Predicate: *`Type`*`Predicate`
- Consumer: *`Type`*`Consumer`

57

Instance method of object

- Method is invoked on the object
  - Parameters are those of the method

```
v -> hexDigits.charAt(v)
```

```
String hexDigits = "0123456789ABCDEF";
IntFunction<Character>
IntToCharFun hex = hexDigits::charAt;
System.out.println("Hex for 10 : "
                   + hex.apply(10) );
```

```
interface IntToCharFun
  char apply(int value)
}
```

```
interface IntFunction<R> {
  R apply(int value);
}
```

58

58

Instance method reference

- The first argument is the object on which the method is invoked
  - The remaining arguments are mapped to the method arguments

```
s -> s.length()
```

```
ToIntFunction<String>
 StringToIntFunction f = String::length;
for(String s : words){
  System.out.println(f.apply(s));
}
```

```
interface ToIntFunction<T> {
  int applyAsInt(T x);
}
```

```
tringToIntFunction {
(String s);
```


59

Constructor reference

- The return type is a new object
  - Parameters are the constructor's parameters

```
i -> new Integer(i);
```

```
IntFunction<Integer>
  IntegerBuilder builder = Integer::new;
                 apply
  Integer i = builder.build(1);
```

```
interface IntFunction<R> {
  R apply(int value);
}
```

```
IntegerBuilder{
er build(int value);
}
```


60

Generic `Comparator`

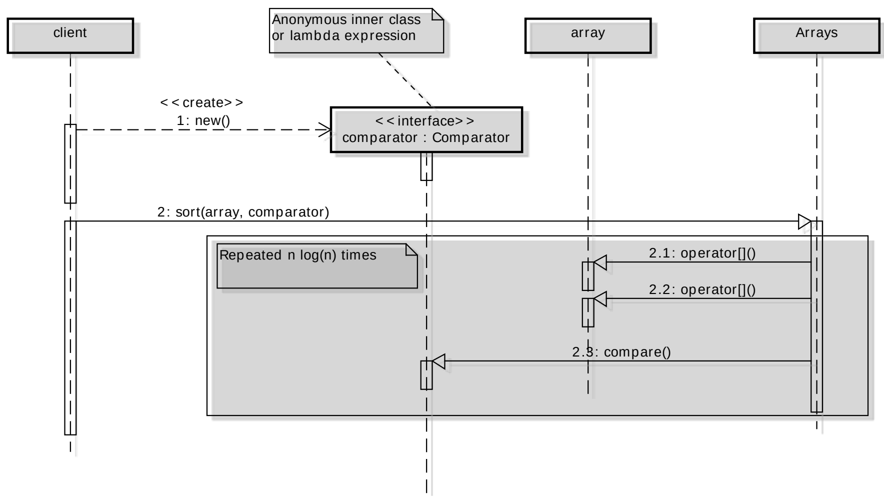
Interface `java.util.Comparator`

```
public interface Comparator<T>{
  int compare(T a, T b);
}
```

```
Arrays.sort(sv, (a,b) -> a.id - b.id );
```

```
Arrays.sort(sv, new Comparator<Student>(){
 public void compare(Student a, Student b){
   return a.id - b.id
 });
```


Comparator behavior



Comparator factory

- Most comparators take some information out of the objects to be compared
  - Typically through a getter
  - Such values are primitive or are comparable using their natural order (i.e. `Comparable`)
- Such comparator can be generated starting from a key getter functional object:

```
static <T,U extends Comparable<U>>
Comparator<T>
   comparing(Function<T,U> keyGetter)
```

Comparator.comparing()

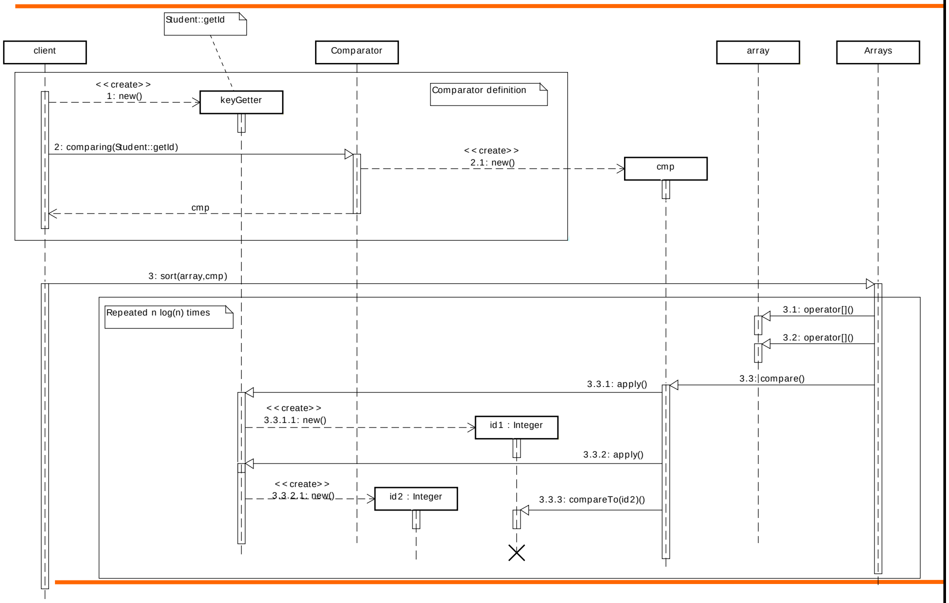
Comparator.comparing

```
Arrays.sort(sv,comparing(Student::getId));
```

Requires:
`import static java.util.Comparator.*`

```
static <T,U extends Comparable<? super U>>
Comparator<T>
  comparing(Function<T,U> keyGetter){
  return (a,b) -> keyGetter.apply(a).
                  compareTo(keyGetter.apply(b));
}
```

Comparator factory behavior



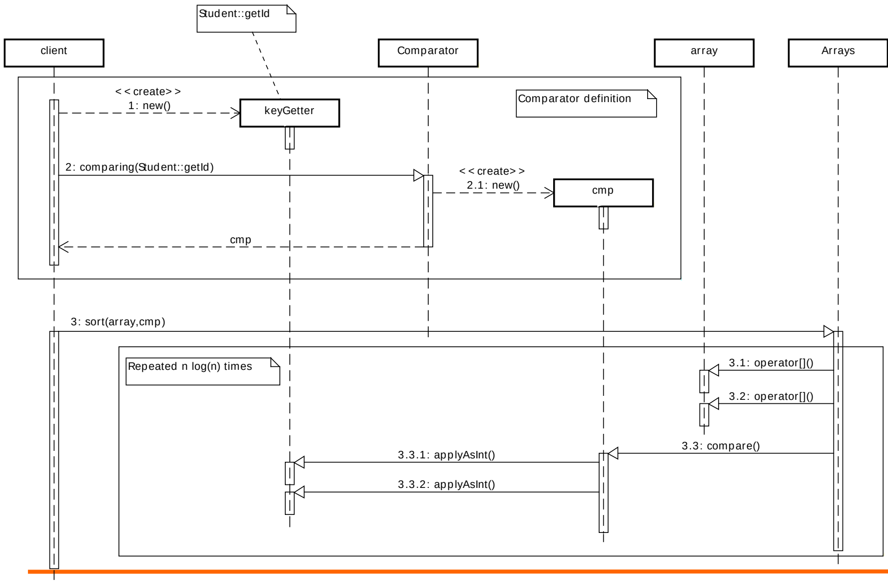
Comparator.comparingInt

```
Arrays.sort(sv,comparingInt(Student::getId))
```

Requires:
`import static java.util.Comparator.*`

```
static <T,U extends Comparable<? super U>>
Comparator<T>
  comparing(ToIntFunction<T,U> keyGetter){
  return (a,b) -> keyGetter.applyAsInt(a) -
                  keyGetter.applyAsInt(b);
}
```

IntComparator factory behavior



Performance

Comparator	Time
`(a,b)-> a.id - b.id`	100
`(a,b)-> a.getId() - b.getId()`	120
`comparingInt(Student::getId)`	135
`comparing(Student::getId)`	185

Relative performance

Also use a lot of memory due to wrapper objects creation

Comparator historical perspective

```
Arrays.sort(sv,new Comparator(){
 public int compare(Object a, Object b){
   return ((Student)a).id-((Student)b).id;
 }});
```

Java ≥ 2

```
Arrays.sort(sv,new Comparator<Student>(){
 public int compare(Student a, Student b){
   return a.getId() - b.getId();
 }});
```

Java ≥ 5, Generics

Java ≥ 8, Lambda

```
Arrays.sort(sv,(a,b)->a.getId()-b.getId());
```

```
Arrays.sort(sv,comparing(Student::getId));
```

Java ≥ 8, Method reference

Functional interface composition

- Reverse order method
  - Not a Comparator method!

```
static <T> Comparator<T>
  reverse(Comparator<T> cmp){
      return (a,b) -> cmp.compare(b,a);
}
```

```
Arrays.sort(sv,reverse(
                comparing(Student::getId));
```

Comparator composition

- Reverse order
  - Default method `Comparator.reversed()`

```
default <T> Comparator<T> reversed(){
  return (a,b) -> this.compare(b,a);
}
```

```
Arrays.sort(sv,
     comparing(Student::getId).reversed());
```


Comparator composition

- Multiple criteria
  - Default method `Comparator.thenComparing()`

```
default <T> Comparator<T>
       thenComparing(Comparator<T> other){
  return (a,b) -> {
       int r = this.compare(a,b);
       if(r!=0) return r;
       else return other.compare(a,b);
}
```

Comparator composition

- Multiple criteria

```
default <U extends Comparable<U>
Comparator<T> thenComparing(Function<T,U> ke){
  return (a,b) -> {
   int r = this.compare(a,b);
   if(r!=0) return r;
   return ke.apply(a).compareTo(ke.apply(b));
}
```


Comparator composition

```
Arrays.sort(sv,(a,b)-> {
    int l = a.last.compareTo(b.last);
    if(l!=0) return l;
    return a.first.compareTo(b.first);
}));
```

```
Arrays.sort(sv,
  comparing(Student::getLast).
  thenComparing(Student::getFirst));
```

Functional Interface Composition

- Predicate
  - `default Predicate<T> and(Predicate<T> o)`
  - `default Predicate<T> or(Predicate<T> o)`
  - `default Predicate<T> negate()`
- Function
  - `default <V> Function<T,V> andThen(Function<R,V> after)`
  - `default <V> Function<V,R> compose(Function<V,T> before)`

Wrap-up

- Generics allow defining type parameter for methods and classes
- The same code can work with several different types
  - Primitive types must be replaced by wrappers
- Generics containers are type invariant
  - Wildcard, ? (read as unknown)
- Generics are implemented by type erasure
  - Checks are performed at compile time