Java Collections Framework

Object-Oriented Programming

https://softeng.polito.it/courses/09CBI

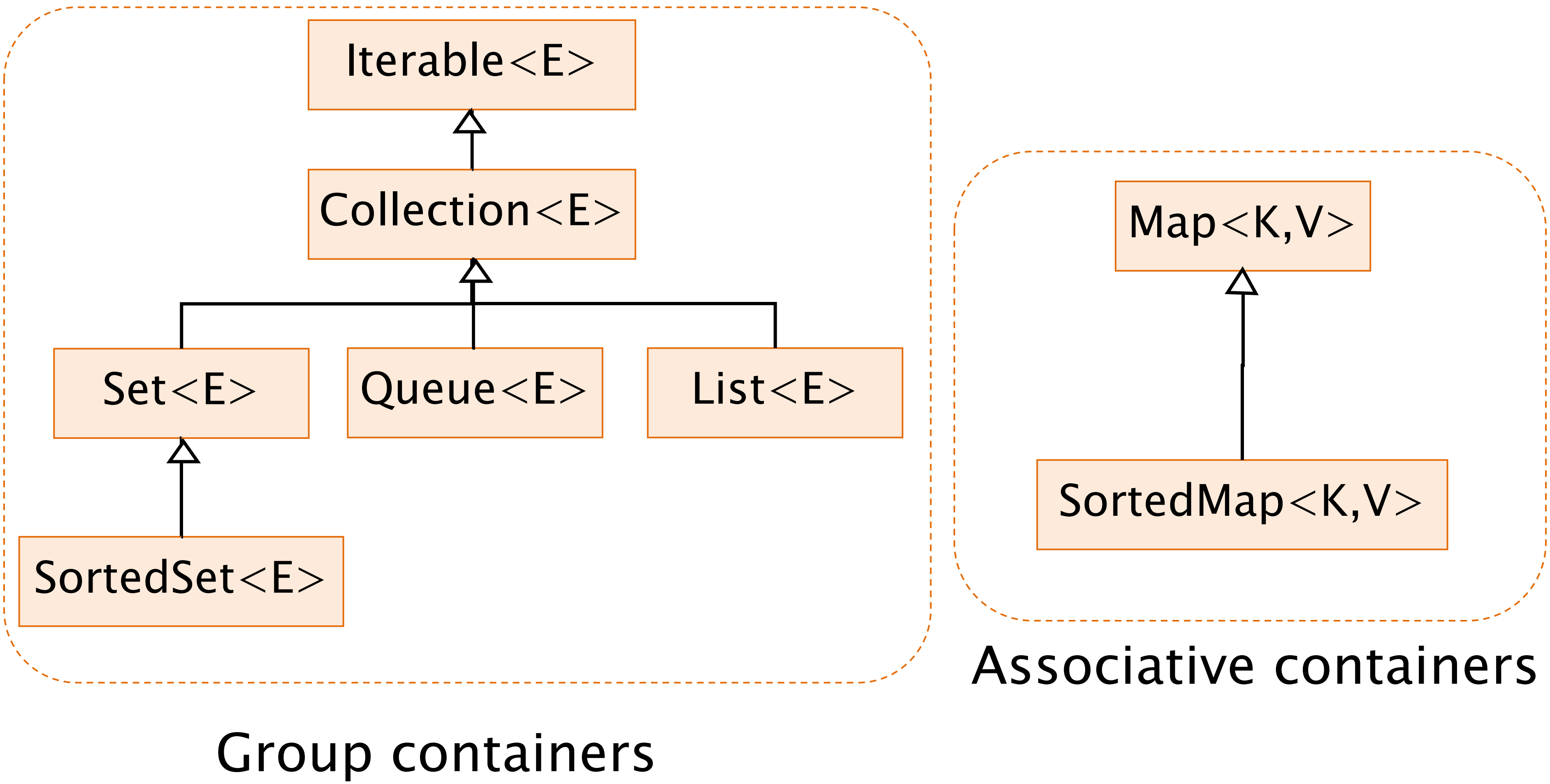
Version 4.1.3

Collections Framework

- Interfaces (ADT, Abstract Data Types)
- Implementations (of ADT)
- Algorithms (sort)
- Contained in the package **`java.util`**

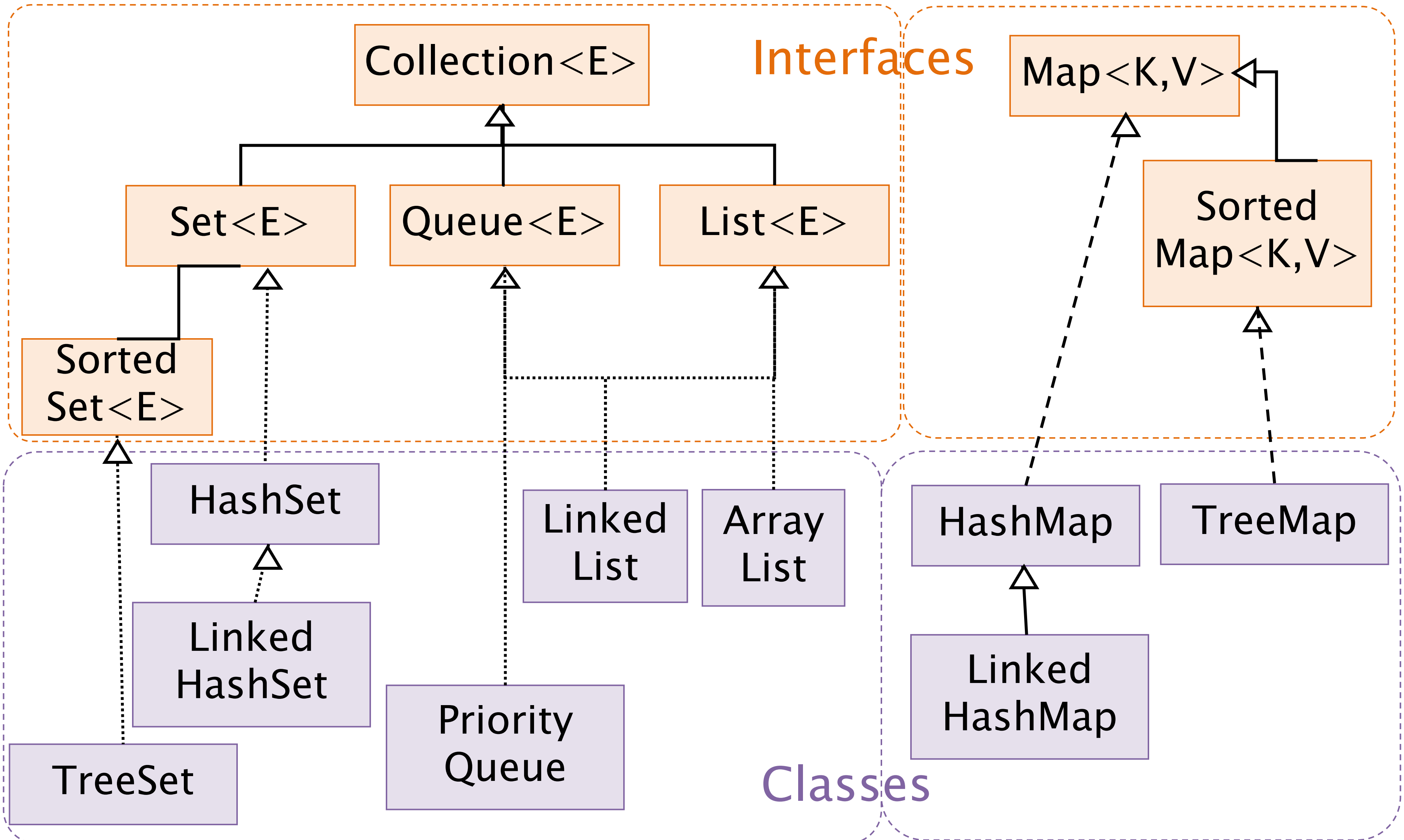
- Originally using **`Object`**, since Java 5 redefined as generic

Interfaces



Iterable<E>
Collection<E>
Set<E>
Queue<E>
List<E>
SortedSet<E>
Map<K,V>
SortedMap<K,V>
Associative containers
Group containers

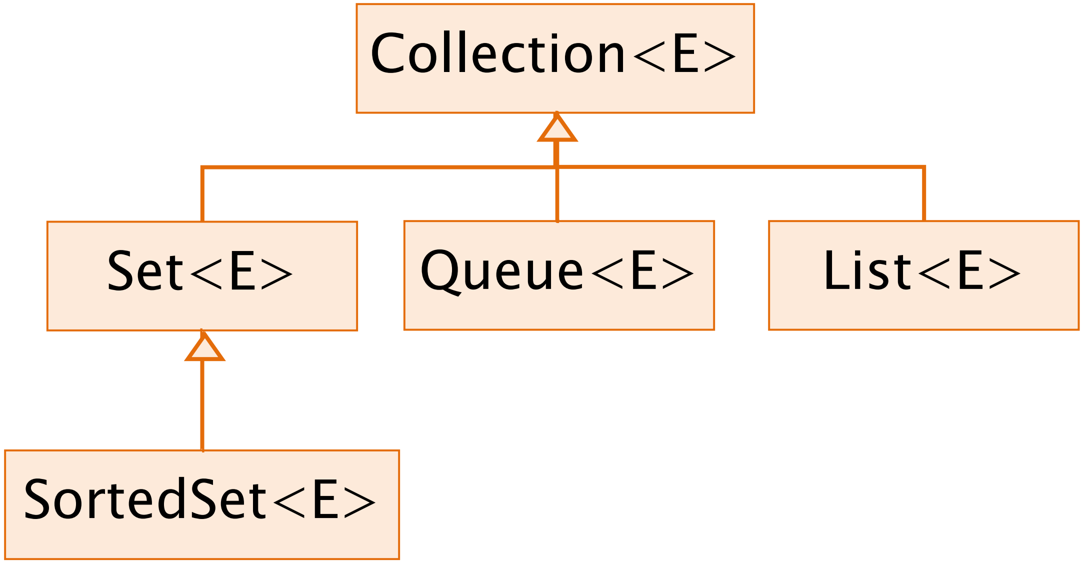
Implementations



Internals

data structure → (rows) ; interface → (columns) ; classes → (cells)

	Set	List	Map
Hash table	`HashSet`		`HashMap`
Balanced tree	`TreeSet`		`TreeMap`
Resizable array		`ArrayList`	
Linked list		`LinkedList`	
HT + LL	`LinkedHashSet`		`LinkedHashMap`



GROUP CONTAINERS (COLLECTIONS)

`Collection`

Set (no duplicates) --> no ordering (only in Sorted Set)
List (can hold duplicates)

- Group of elements (references to objects)
- It is not specified whether they are
  - Ordered / not ordered
  - Duplicated / not duplicated
- Implements **`Iterable`**
- All classes implementing **`Collection`** shall provide two constructors
  - **`C()`**
  - **`C(Collection c)`** to create a copy of the collection c

`Collection` interface

```
int size()
boolean isEmpty()
boolean contains(E element)
boolean containsAll(Collection<?> c)
boolean add(E element)
boolean addAll(Collection<? extends E> c)
boolean remove(E element)
boolean removeAll(Collection<?> c)
void clear()
Object[] toArray()
Iterator<E> iterator()
```

Collection example

```
Collection<Person> persons =
                new LinkedList<Person>();
persons.add( new Person(“Alice”) );
System.out.println( persons.size() );
Collection<Person> copy =
                   new TreeSet<Person>();
copy.addAll(persons);//new TreeSet(persons)
Person[] array = copy.toArray();
System.out.println( array[0] );
```

`List`

- Can contain duplicate elements
- Insertion order is preserved
- User can define insertion point
- Elements can be accessed by position
- Augments `Collection` interface

`List` interface

```
E get(int index)
E set(int index, E element)
void add(int index, E element)
E remove(int index)

boolean addAll(int index,Collection<E> c)
int indexOf(E o)
int lastIndexOf(E o)
List<E> subList(int from, int to)
```

`List` implementations

- **`ArrayList<E>`**
  - `ArrayList()`
  - `ArrayList(int initialCapacity)`
  - `ArrayList(Collection<E> c)`
  - `void ensureCapacity(int minCapacity)`
- **`LinkedList<E>`**
  - `void addFirst(E o)`
  - `void addLast(E o)`
  - `E getFirst()`
  - `E getLast()`
  - `E removeFirst()`
  - `E removeLast()`

Example

```
List<Integer> l = new ArrayList<>();

l.add(42);             // 42 in position 0
l.add(0, 13);          // 42 moved to position 1
l.set(0, 20);          // 13 replaced by 20
int a = l.get(1);  // returns 42
l.add(9, 30);           // NO: out of bounds
```

IndexOutOfBoundsException

`Queue` interface

- Collection whose elements are inserted using an
  - Insertion order (FIFO)
  - Element order (Priority queue)
- Defines a head position where is the first element that can be accessed
  - `peek()`
  - `poll()`

`Queue` implementations

- **`LinkedList`**
  - head is the first element of the list
  - FIFO: Fist-In-First-Out
- **`PriorityQueue`**
  - head is the smallest element

`Queue` example

```
Queue<Integer> fifo =
            new LinkedList<Integer>();

Queue<Integer> pq =
            new PriorityQueue<Integer>();

fifo.add(3); pq.add(3);
fifo.add(1); pq.add(1);
fifo.add(2); pq.add(2);

System.out.println(fifo.peek()); // 3

System.out.println(pq.peek());   // 1
```

`Set` interface

- Contains no methods
  - Only those inherited from `Collection`
- `add()` has the restriction that no duplicate elements are allowed
  - `e1.equals(e2) == false` $\forall$ e1,e2 $\in \Sigma$
- Iterator
  - The elements are traversed in no particular order

`SortedSet` interface

- No duplicate elements
- Iterator
  - The elements are traversed according to the natural ordering (ascending)
- Augments Set interface
  - `E first()`
  - `E last()`
  - `SortedSet<E> headSet(E toElement)`
  - `SortedSet<E> tailSet(E fromElement)`
  - `SortedSet<E> subSet(E from, E to)`

`Set` implementations

- `HashSet` implements `Set`
  - Hash tables as internal data structure (faster)
- `LinkedHashSet` extends `HashSet`
  - Elements are traversed by iterator according to the insertion order
- `TreeSet` implements `SortedSet`
  - R-B trees as internal data structure (computationally expensive)

Note on sorted collections

- Depending on the constructor used they require different implementation of the custom ordering
- **`TreeSet()`**
  - Natural ordering (elements must be implementations of Comparable)
- **`TreeSet(Comparator c)`**
  - Ordering is according to the comparator rules, instead of natural ordering

ITERATORS

`Iterable` interface

- Container of elements that can be iterated upon
- Provides a single instance method:

```
Iterator<E> iterator()
```

  - It returns the iterator on the elements of the collection
- Collection extends Iterable

Iterators and iteration

- A common operation with collections is to iterate over their elements
- Interface Iterator provides a transparent means to cycle through all elements of a Collection
- Keeps track of last visited element of the related collection
- Each time the current element is queried, it moves on automatically

`Iterator`

- Allows the iteration on the elements of a collection
- Two main methods:
  - `boolean hasNext()`
    - Checks if there is a next element to iterate on
  - `E next()`
    - Returns the next element and advances by one position
  - `void remove()`
    - Optional method, removes the current element

`Iterator` examples

Print all objects in a list

```
Iterable<Person> persons =
                    new LinkedList<Person>();
…
for(Iterator<Person> i = persons.iterator();
                          i.hasNext(); ) {
   Person p = i.next();
   …
  System.out.println(p);
}
```

`Iterator` examples

The for-each syntax avoids
using iterator directly

```
Iterable<Person> persons =
                  new LinkedList<Person>();
…
for(Person p: persons) {
   …
  System.out.println(p);
}
```

Iterable `forEach`

- Iterable defines the default method

  `forEach(Consumer<? super T> action)`
- Can be used to perform operations of elements with a functional interface

```
Iterable<Person> persons;
…
persons.forEach( p -> {
  System.out.println(p);
});
```

Note well

- It is unsafe to iterate over a collection you are modifying (add/remove) at the same time

- Unless you are using the iterator's own methods
  - `Iterator.remove()`
  - `ListIterator.add()`

Delete

```
List<Integer> lst=new LinkedList<>();
lst.add( 10 );
lst.add( 11 );
lst.add( 13 );
lst.add( 20 );

int count = 0;
for (Iterator<?> itr = lst.iterator();
                                  itr.hasNext(); ) {
    itr.next();
    if (count==1)
        lst.remove(count); // wrong
    count++;
}
```

ConcurrentModificationException

Delete (cont'd)

```
List<Integer> lst = new LinkedList<>();
lst.add( 10 );
lst.add( 11 );
lst.add( 13 );
lst.add( 20 );

int count = 0;
for (Iterator<?> itr = lst.iterator();
                       itr.hasNext(); ) {
    itr.next();
    if (count==1)
        itr.remove(); // ok
    count++;
}
```

Correct

Add

```
List<Integer> lst = new LinkedList<>();
lst.add( 10 );
lst.add( 11 );
lst.add( 13 );
lst.add( 20 );

int count = 0;
for (Iterator itr = lst.iterator();
                    itr.hasNext(); ) {
   itr.next();
   if (count==2)
     lst.add(count, 22 );//wrong
   count++;
}
```

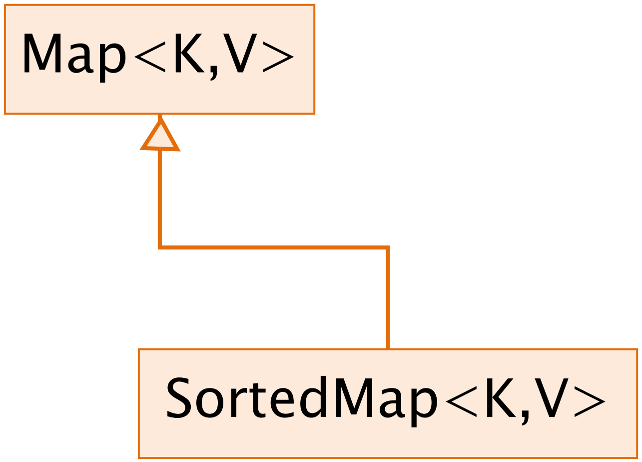
ConcurrentModificationException

Add (cont’d)

```
List<Integer> lst = new LinkedList<>();
lst.add( 10 );
lst.add( 11 );
lst.add( 13 );
lst.add( 20 );

int count = 0;
for (ListIterator<Integer> itr =
      lst.listIterator(); itr.hasNext();){
   itr.next();
   if (count==2)
      itr.add(new Integer(22)); // ok
   count++;
}
```

Correct



ASSOCIATIVE CONTAINERS (MAPS)

`Map`

- A container that associates keys to values (e.g., SSN ⇒ Person)
- Keys and values must be objects
- Keys must be unique
  - Only one value per key

- Following constructors are common to all collection implementers
  - **`M()`**
  - **`M(Map m)`**

`Map` interface

- `V put(K key, V value)`
- `V get(K key)`
- `Object remove(K key)`
- `boolean containsKey(K key)`
- `boolean containsValue(V value)`
- `public Set<K> keySet()`
- `public Collection<V> values()`
- `int size()`
- `boolean isEmpty()`
- `void clear()`

Map example: `put` and `get`

```
Map<String,Person> people =new HashMap<>();
people.put( “ALCSMT”, //ssn
   new Person(“Alice”, “Smith”) );
people.put( “RBTGRN”, //ssn
   new Person(“Robert”, “Green”) );

if( ! people.containsKey(“RBTGRN”))
  System.out.println( “Not found” );

Person bob = people.get(“RBTGRN”);

int populationSize = people.size();
```

Map ex.: values and keySet

```
Map<String,Person> people =new HashMap<>();
people.put( "ALCSMT", //ssn
  new Person("Alice", "Smith") );
people.put("RBTGRN", //ssn
  new Person("Robert", "Green") );
// Print all people
for(Person p : people.values()){
  System.out.println(p);
}
// Print all ssn
for(String ssn : people.keySet()){
  System.out.println(ssn);
}
```

`SortedMap` interface

- The elements are traversed according to the keys' natural ordering
  - Or using comparator passed to ctor
- Augments `Map` interface
  - `SortedMap subMap(K fromKey, K toKey)`
  - `SortedMap headMap(K toKey)`
  - `SortedMap tailMap(K fromKey)`
  - `K firstKey()`
  - `K lastKey()`

`Map` implementations

- Similar to `Set`
- `HashMap` implements `Map`
  - No order
- `LinkedHashMap` extends `HashMap`
  - Insertion order
- `TreeMap` implements `SortedMap`
  - Ascending key order

OPTIONAL

Nullability problem

- The typical convention in Java APIs is to let a method return a **`null`** reference to represent the absence of a result.
- The caller must check the return value of the method to detect that case
- In absence of checks *NPE*s may occur
  - *NPE* is **`NullPointerException`**

`Optional`

- `Optional` is a class used to represent a potential value
- Methods returning `Optional<T>` make explicit that the return value may be missing
  - Forces the clients to deal with potentially empty optional

`Optional<T>`

- Access to embedded value through
  - **`boolean isPresent()`**
    - checks if Optional contains a value
  - **`ifPresent(Consumer<T> block)`**
    - executes the given block if a value is present.
  - **`T get()`**
    - returns the value if present; otherwise it throws a **`NoSuchElementException`**.
  - **`T orElse(T default)`**
    - returns the value if present; otherwise it returns a **`default`** value.
  - **`T orElse(Supplier<T> s)`**
    - when empty return the value supplied value by **`s`**

`Optional<T>`

- Creation uses static factory methods:
  - **`of(T v)`**:
    - throw exception if **`v`** is **`null`**
  - **`ofNullable(T v)`**:
    - returns an empty Optional when **`v`** is **`null`**
  - **`empty()`**
    - returns an empty Optional
  - Such methods force the programmer to think about what he’s about to return

Using Collections

Use general interfaces

- E.g. **`List<>`** is better than **`LinkedList<>`**
- General interfaces are more flexible for future changes
- Makes you think
  - First about the type of container
  - Then about the implementation

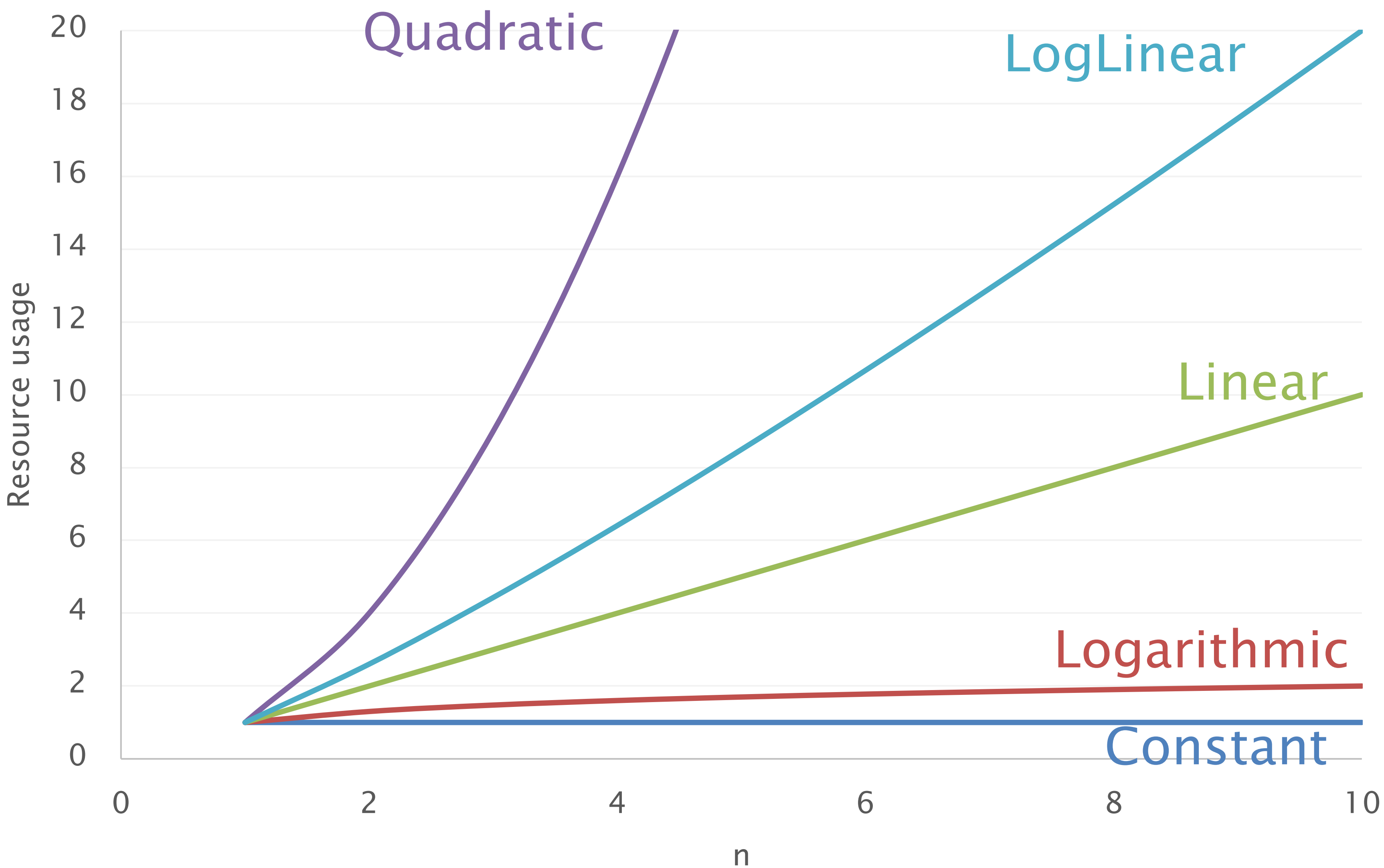
Selecting the container type

- If access by key is needed use a **`Map`**
  - If values sorted by key use a **`SortedMap`**
- Otherwise use a **`Collection`**
  - If indexed access, use a **`List`**
    - Class depends on expected typical operation
  - If access in order, use a **`Queue`**
  - If no duplicates, use a **`Set`**
    - If elements sorted, use a **`SortedSet`**

Efficiency

- Time and Space
- Computed as a function of the number (n) of elements contained
  - Constant: independent of n
  - Logarithmic: grows as $log(n)$
  - Linear: grows proportionally to n
  - Loglinear: grows as $n\ log(n)$
  - Quadratic: grows proportionally to n^2

Efficiency



Quadratic
LogLinear
Linear
Logarithmic
Constant
Resource usage
n
0
2
4
6
8
10
12
14
16
18
20

`List` implementations

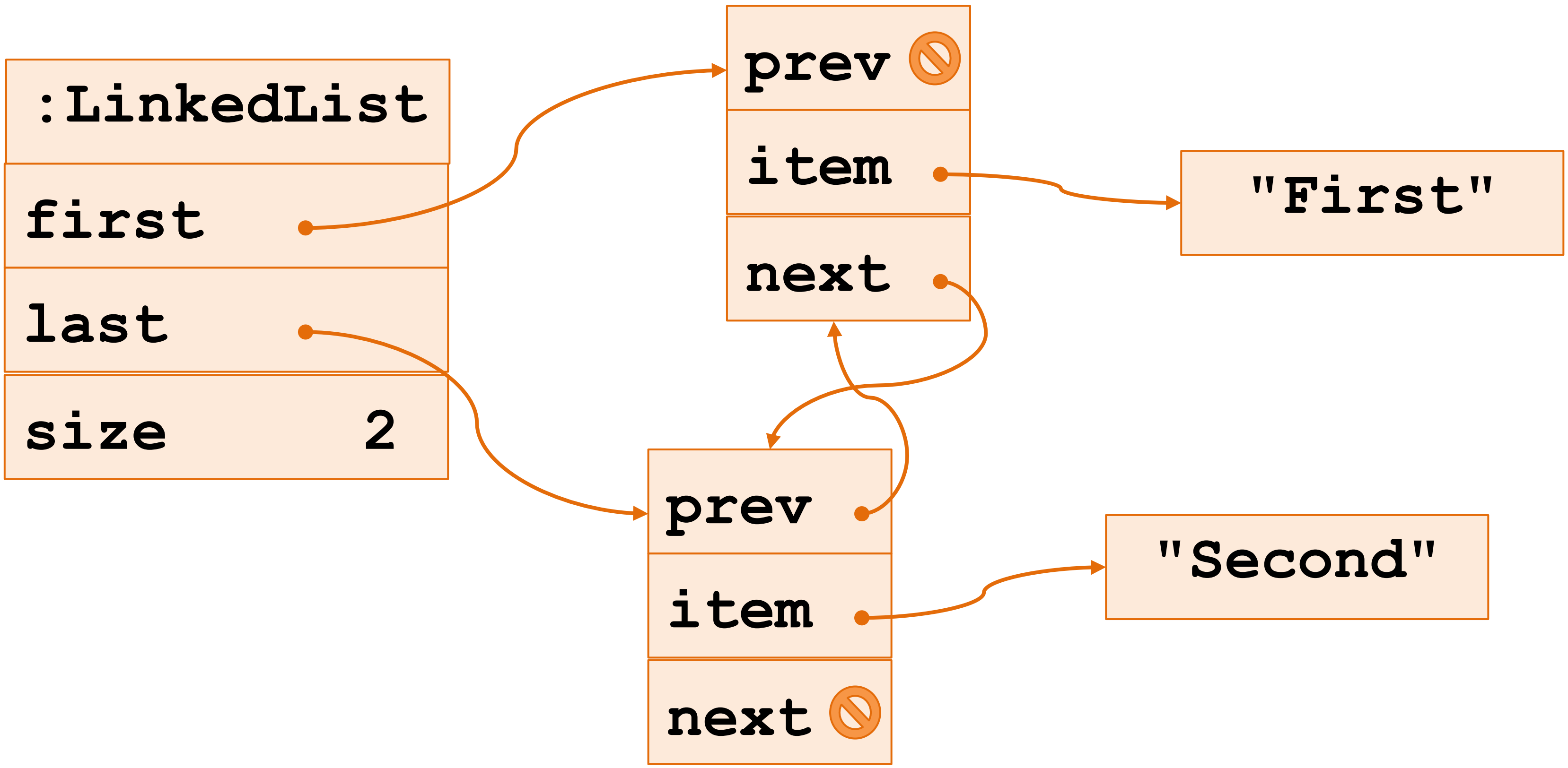
`ArrayList`

- **`get(n)`**
  - Constant
- **`add(0,…)`**
  - Linear
- **`add()`**
  - Constant

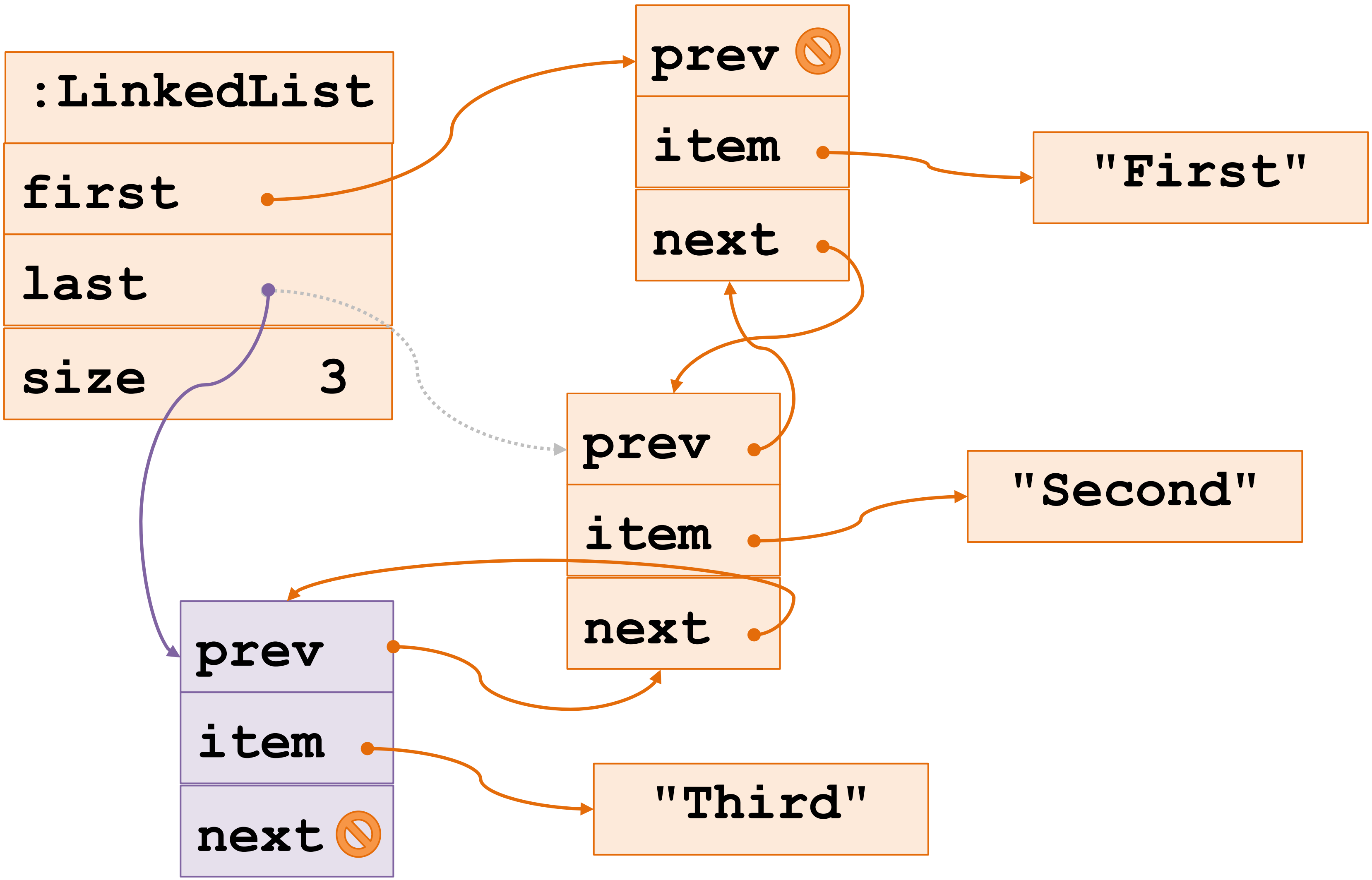
`LinkedList`

- **`get(n)`**
  - Linear
- **`add(0, … )`**
  - Constant
- **`add()`**
  - Constant

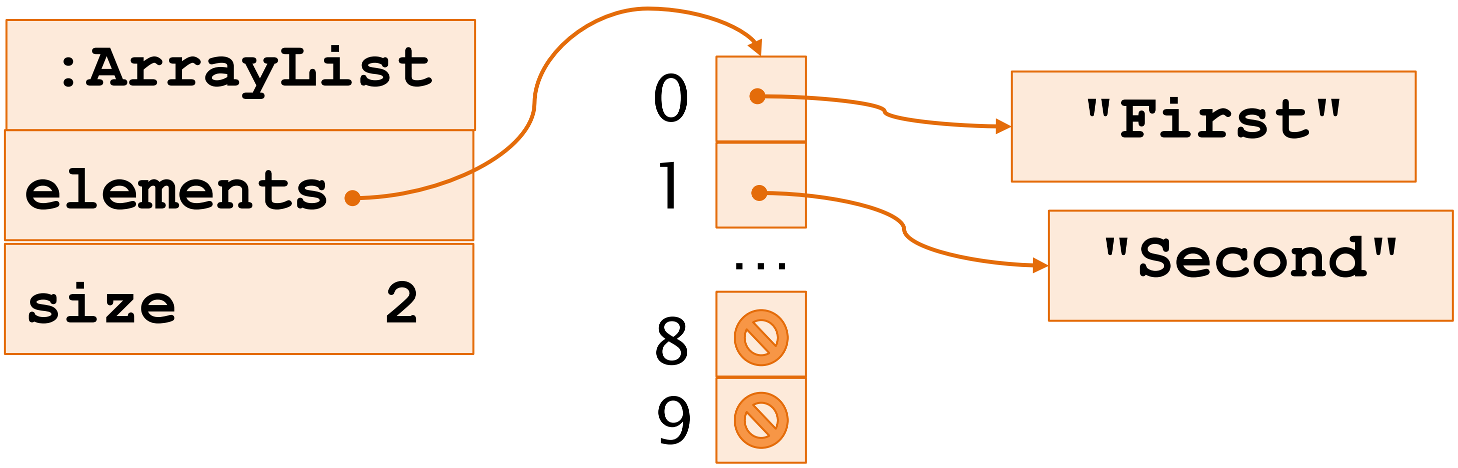
Linked list


:LinkedList
first
last
size 2
prev
item
next
"First"
prev
item
next
"Second"

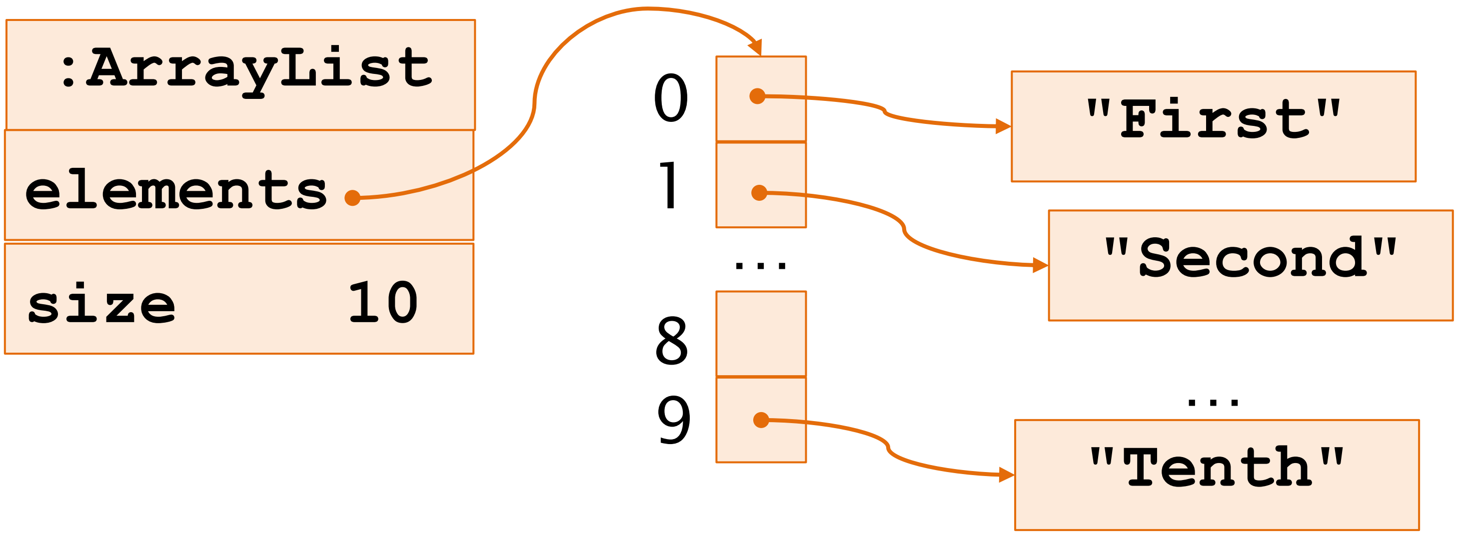
Linked list


:LinkedList
first
last
size 3
prev
item
next
"First"
prev
item
next
"Second"
prev
item
next
"Third"

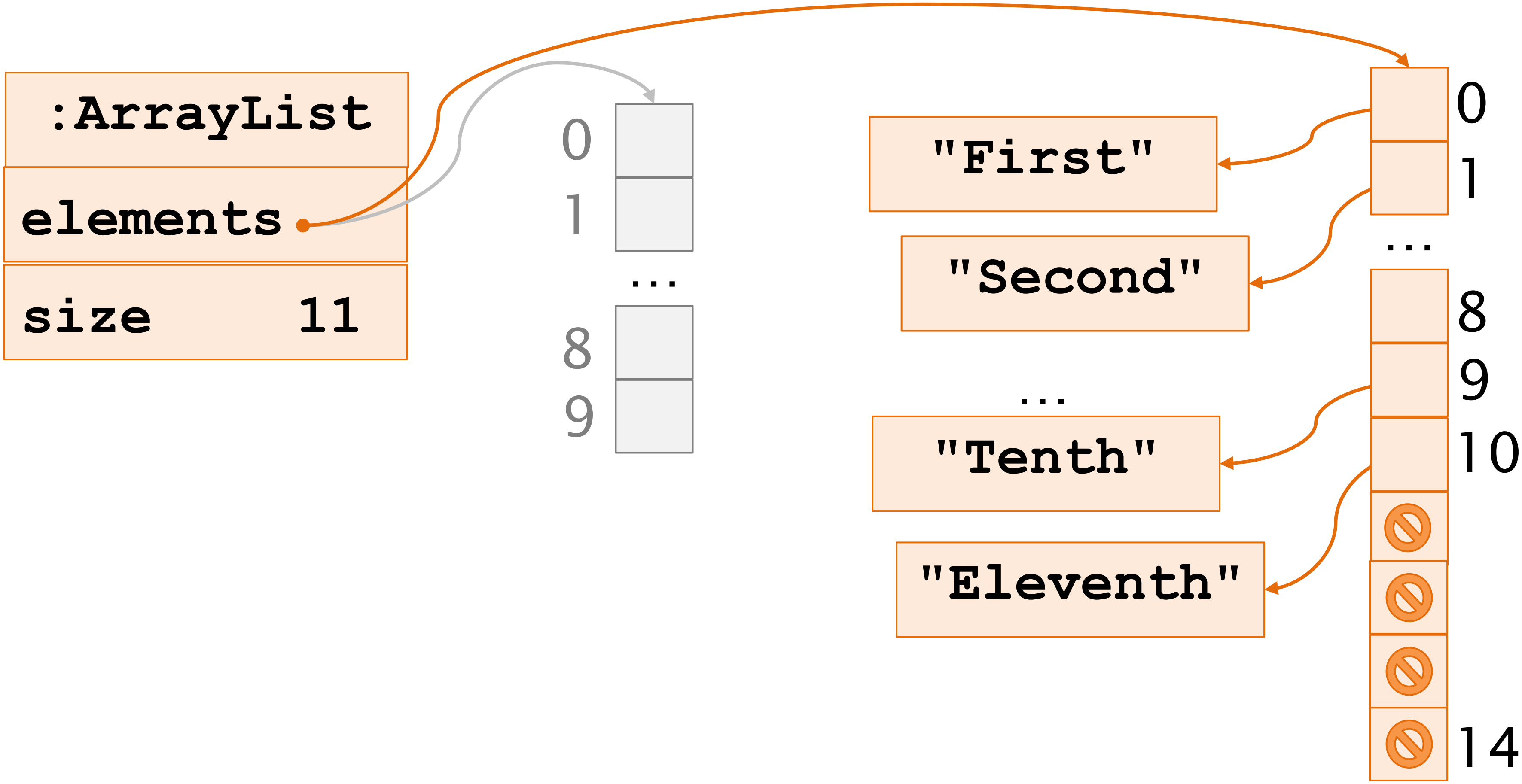
Array list



Array list

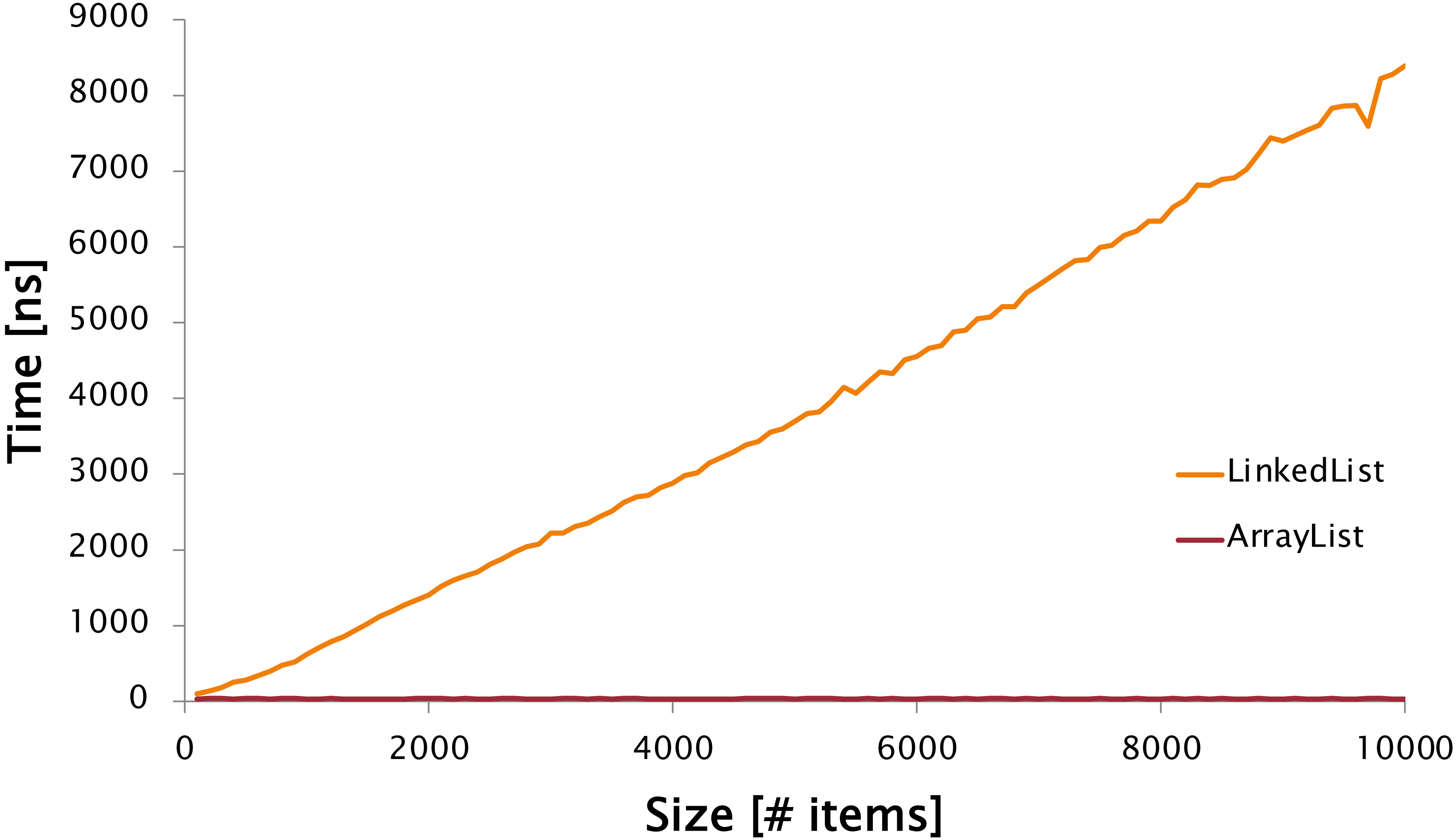


Array list

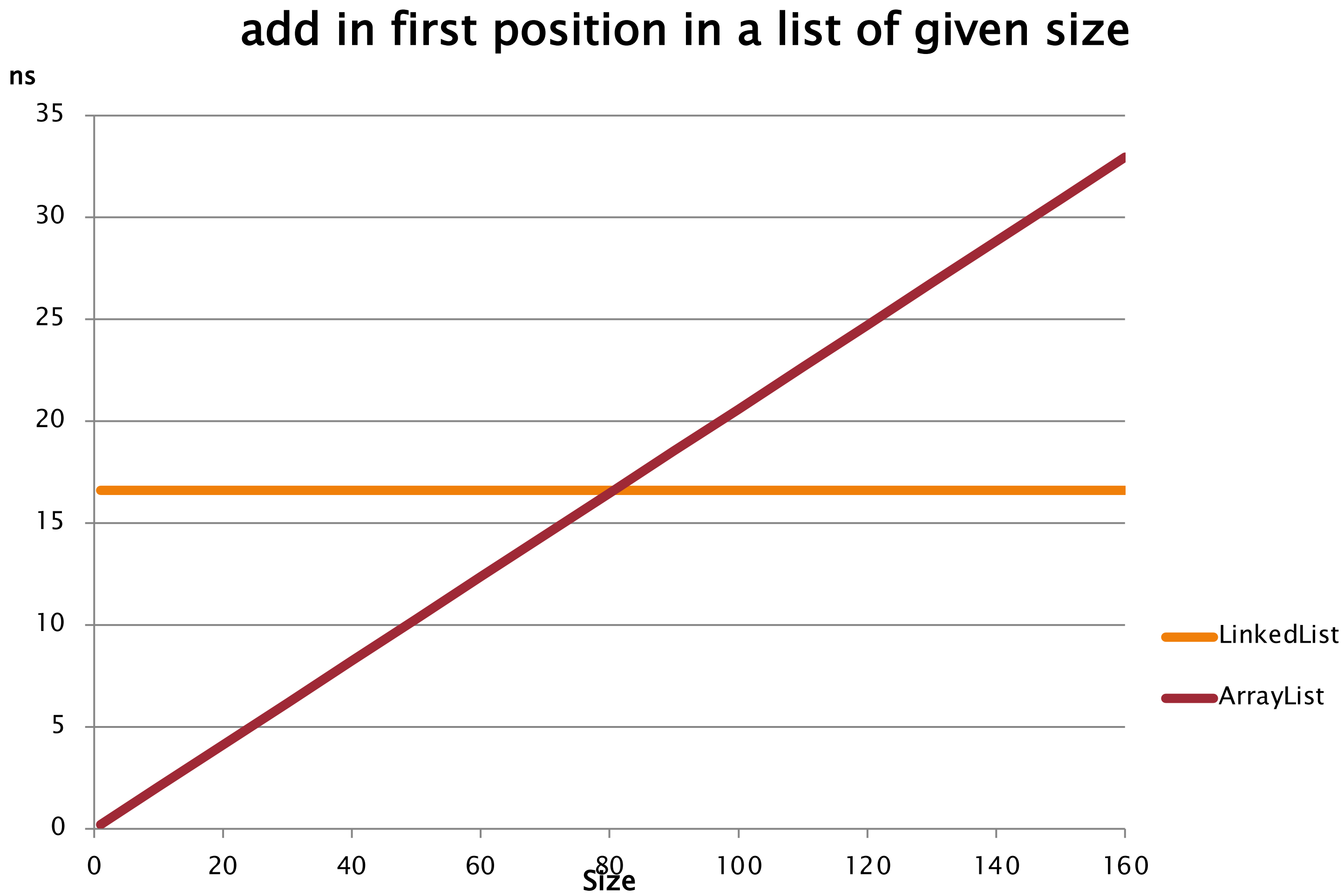


:ArrayList
elements
size 11
0
1
...
8
9
"First"
"Second"
...
"Tenth"
"Eleventh"
0
1
...
8
9
10
14

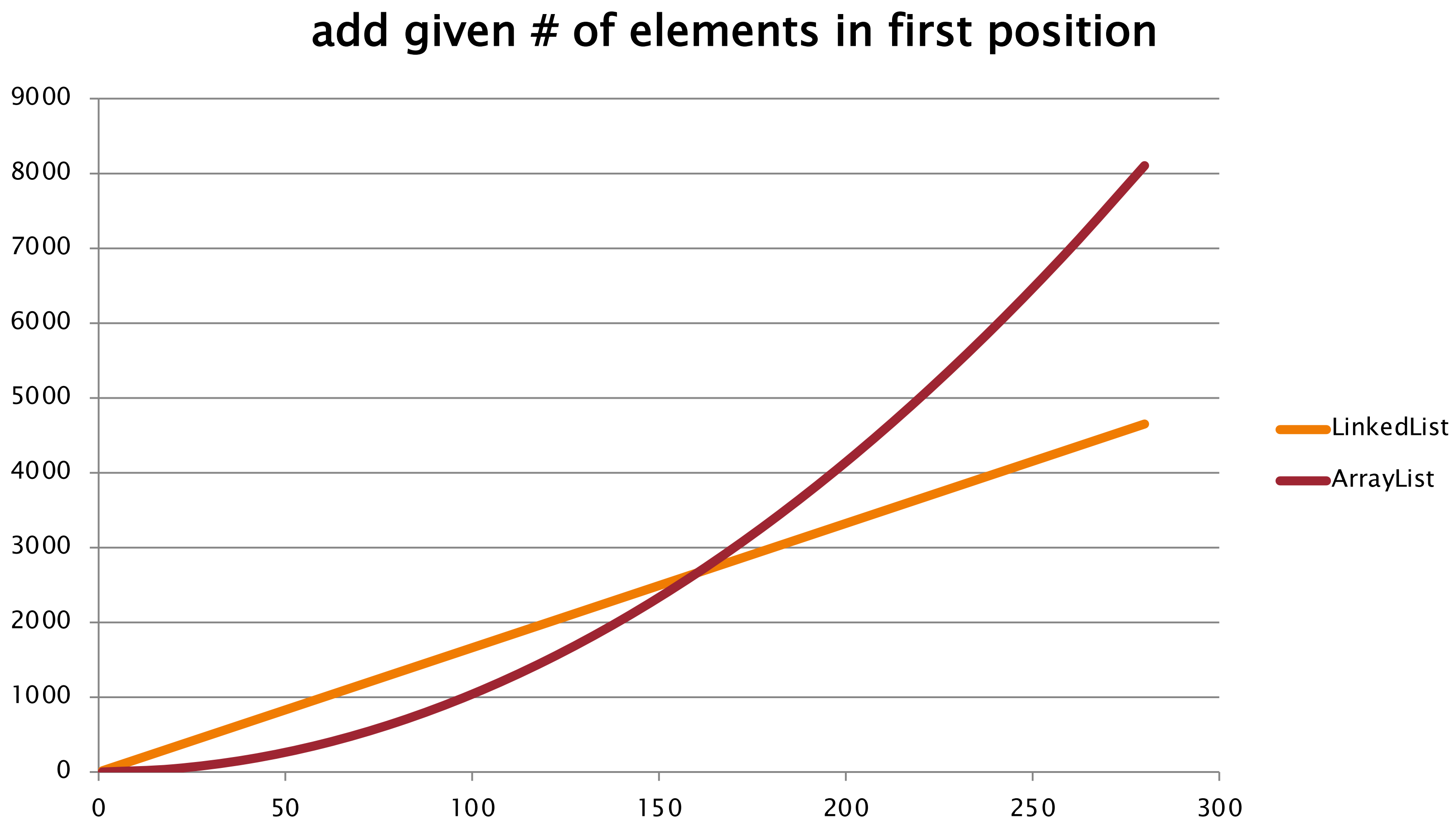
`List` implementations – Get



`List` Implementations – Add



`List` Implementations – Add



`List` implementation – Models

	`LinkedList`	`ArrayList`
Add in first pos. in list of size *n*	$t(n) = C_L$	$t(n) = n \cdot C_A$
Add *n* elements	$t(n) = n \cdot C_L$	$t(n) = \sum_{i=1}^{n} C_A \cdot i = \frac{C_A}{2} n \cdot (n-1)$

$C_L =$ 16.0 ns

$C_A =$ 0.2 ns

Using maps

- Getting an item

```
String val = map.get(key);
if( val == null ) {
    // not found
}
```

- Or

```
if( ! map.containsKey(key)) {
    // not found
}
String val = map.get(key);
```

Using maps

- Updating entries
  - E.g. counting frequencies

```
Map<String,Integer> wc=new XMap<>();
for(String w : words) {
   Integer i= wc.get(w);
  wc.put(w, i==null?1:i+1);
}
```

Using maps

- Updating entries
  - E.g. counting frequencies

```
Map<String,Integer> wc=new XMap<>();
for(String w : words) {
   wc.compute(w,(k,v)->v==null?1:v+1);
}
```

Autoboxing hides memory fee of 16 bytes per increment due to object creation: `Integer.valueOf(v.intValue()+1)`

Using maps

```
class Counter {
  int i=0;
  public String
  toString(){
   return ":"+i; }
}
```

- Updating entries
  - E.g. counting frequencies

```
Map<String,Counter> wc=new XMap<>();
for(String w : words) {
  wc.computeIfAbsent(w,
                 k->new Counter()).i++;
}
```

~40% faster than with `Integer`
– 16 bytes per each increment

Using maps

- Keeping items sorted
  - Using sorted maps

```
SortedMap<…> wc=new TreeMap<>();
```

  - “A”=1, “All”=3, “And"=2, “Barefoot”=1,…

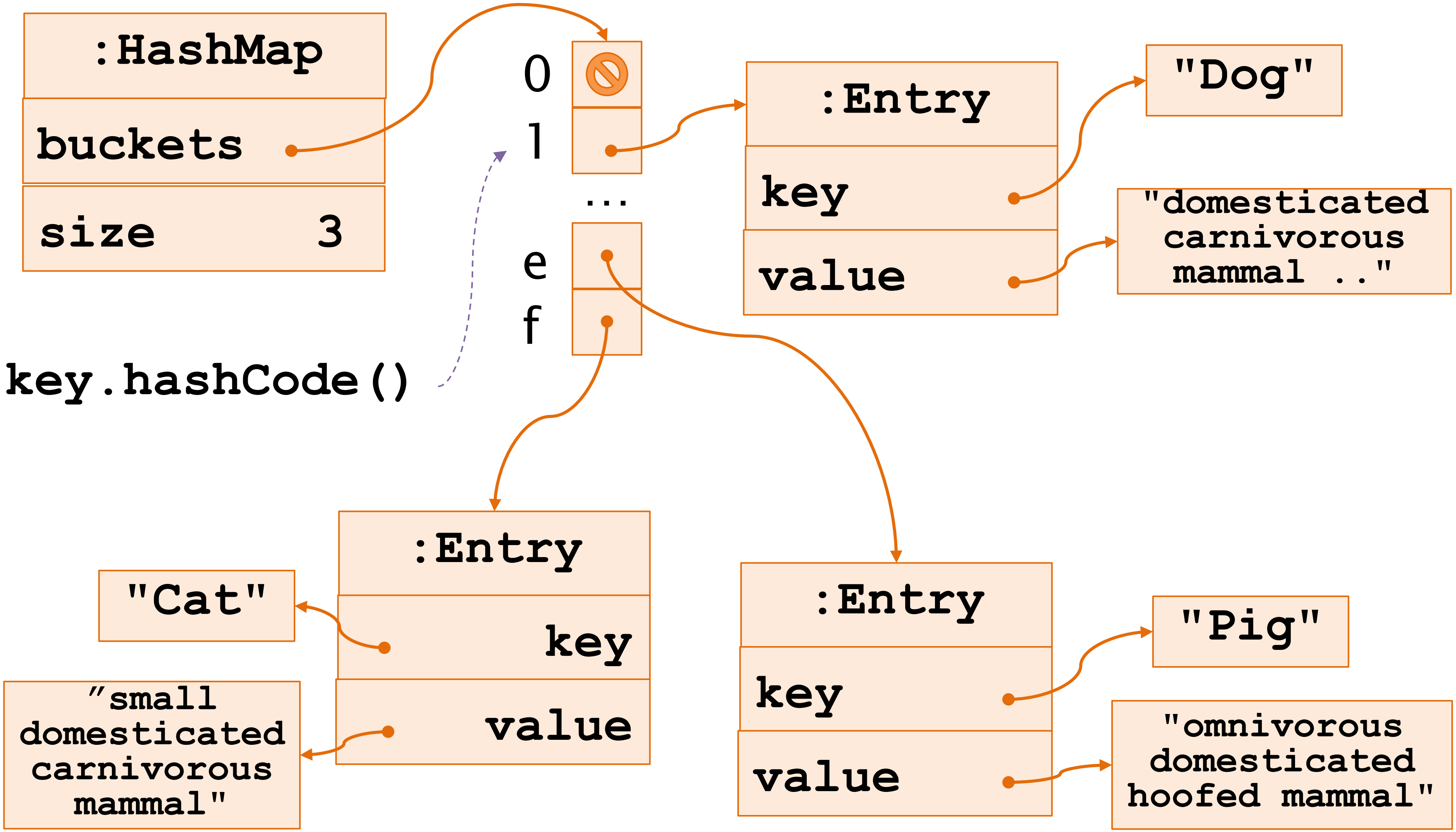
```
Map<…> wc=new HashMap<>();
```

  - “reason”=1, “been”=1, “spoke”=1, “let”=1

HashMap

- Get/put takes constant time (in case of no collisions)
- Automatic re-allocation when load factor reached
- Constructor optional arguments
  - load factor (default = .75)
  - initial capacity (default = 16)

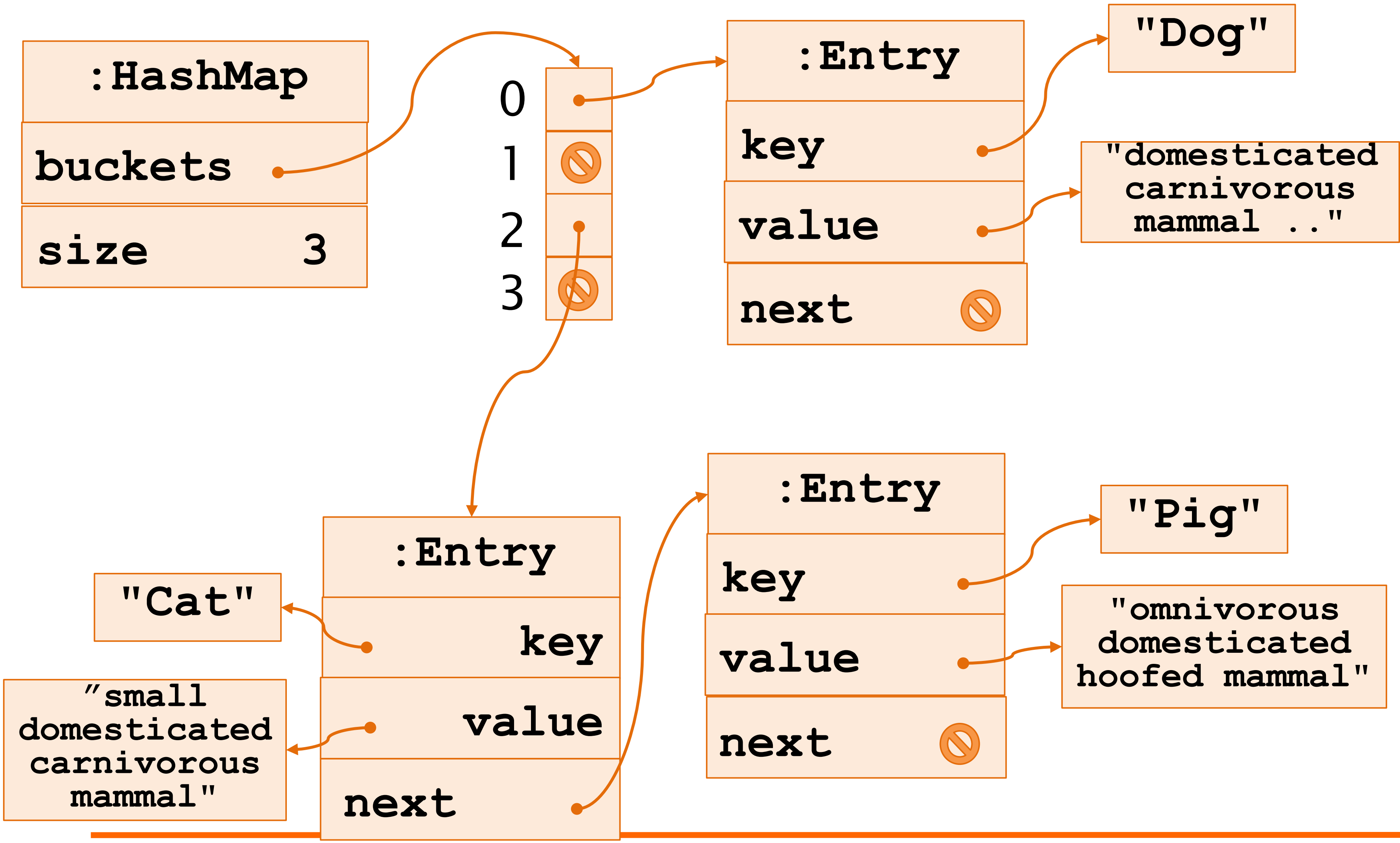
Hashmap


:HashMap
buckets
size 3
0
1
...
e
f
key.hashCode()
:Entry
key
value
"Dog"
"domesticated carnivorous mammal .."
:Entry
key
value
"Cat"
"small domesticated carnivorous mammal"
:Entry
key
value
"Pig"
"omnivorous domesticated hoofed mammal"

Hash limitations

- Hash based containers **`HashMap`** and **`HashSet`** work better if entries define a suitable **`hashCode()`** method
  - Values must be as spread as possible
  - Otherwise, collisions occur
    - When two entries fall in the same bucket
    - In such a case elements are put in a chained in a list
    - Chaining reduces time efficiency

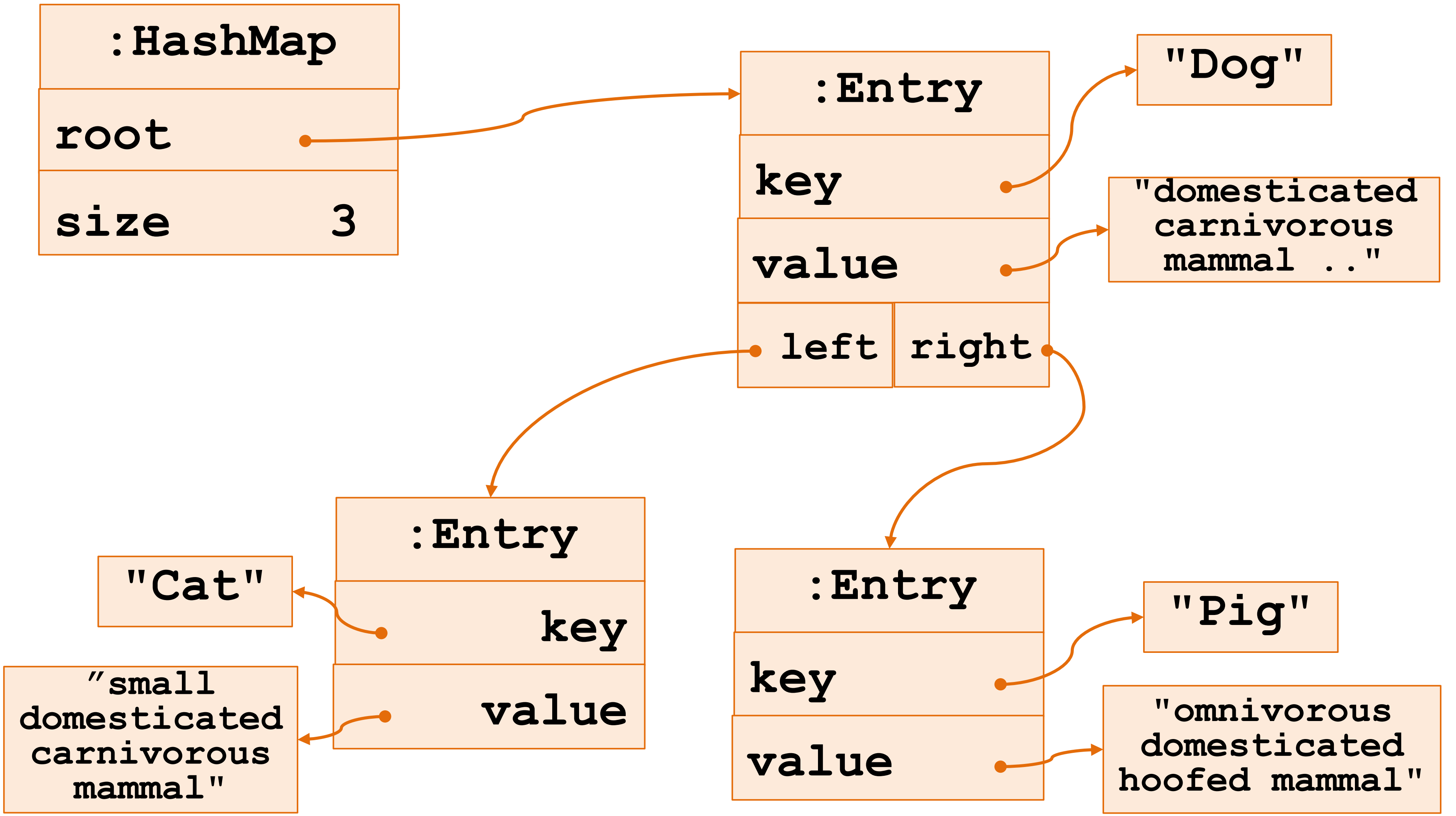
Hashmap (chaining)



`TreeMap`

- Based on a Red-Black tree
- Get/put takes log time
- Keys are maintained and will be traversed in order
  - Key class must be **`Comparable`**
  - Or a **`Comparator`** must be provided to the constructor

TreeMap


:HashMap
root
size 3
:Entry
key
value
left
right
"Dog"
"domesticated carnivorous mammal .."
:Entry
key
value
"Cat"
"small domesticated carnivorous mammal"
:Entry
key
value
"Pig"
"omnivorous domesticated hoofed mammal"

Tree limitations

- Tree based containers (`TreeMap` and `TreeSet`) require either
  - Entries with a natural order (`Comparable`)
  - A `Comparator` to sort entries
- `TreeMap` maintains keys sorted, and return values sorted by key

Search efficiency

- Example:
  - 100k searches in a container require

size	HashMap	TreeMap	ArrayList	LinkedList
100k	3ms	60ms	40s	>1h
200k	3ms	65ms	110s	

ALGORITHMS

Algorithms

- Static methods of `java.util.Collections`
  - Work on List since it has the concept of position
- `sort()` – merge sort of List, $n\ log(n)$
- `binarySearch()` – requires ordered sequence
- `shuffle()` – unsort
- `reverse()` – requires ordered sequence
- `rotate()` – of given a distance
- `min()`, `max()` – in a Collection

`sort()` method

- Operates on `List<T>`
  - Needs access by index to sort
- Two variants:

```
<T extends Comparable<? super T>>
void sort(List<T> list)

<T> void sort(List<T> list,
          Comparator<? super T> cmp)
```

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
    - It does not implement **Comparable<MasterStudent>**
    - But **MasterStudent** extends (indirectly) **Comparable<Student>**

Search

- `<T> int binarySearch(List<? extends Comparable<? super T>> l, T key)`
  - Searches the specified object
  - List must be sorted into ascending order according to natural ordering
- `<T> int binarySearch(List<? extends T> l, T key, Comparator<? super T> c)`
  - Searches the specified object
  - List must be sorted into ascending order according to the specified comparator

Wrap-up

- The collections framework includes interfaces and classes for containers
- There are two main families
  - Group containers
  - Associative containers
- All the components of the framework are defined as generic types