Basic Data-Structures & Algorithms Complexity

This document:
https://github.com/Arnaud-Nauwynck/presentations/blob/main/java/Basic-Data-Structures.pdf

Outline

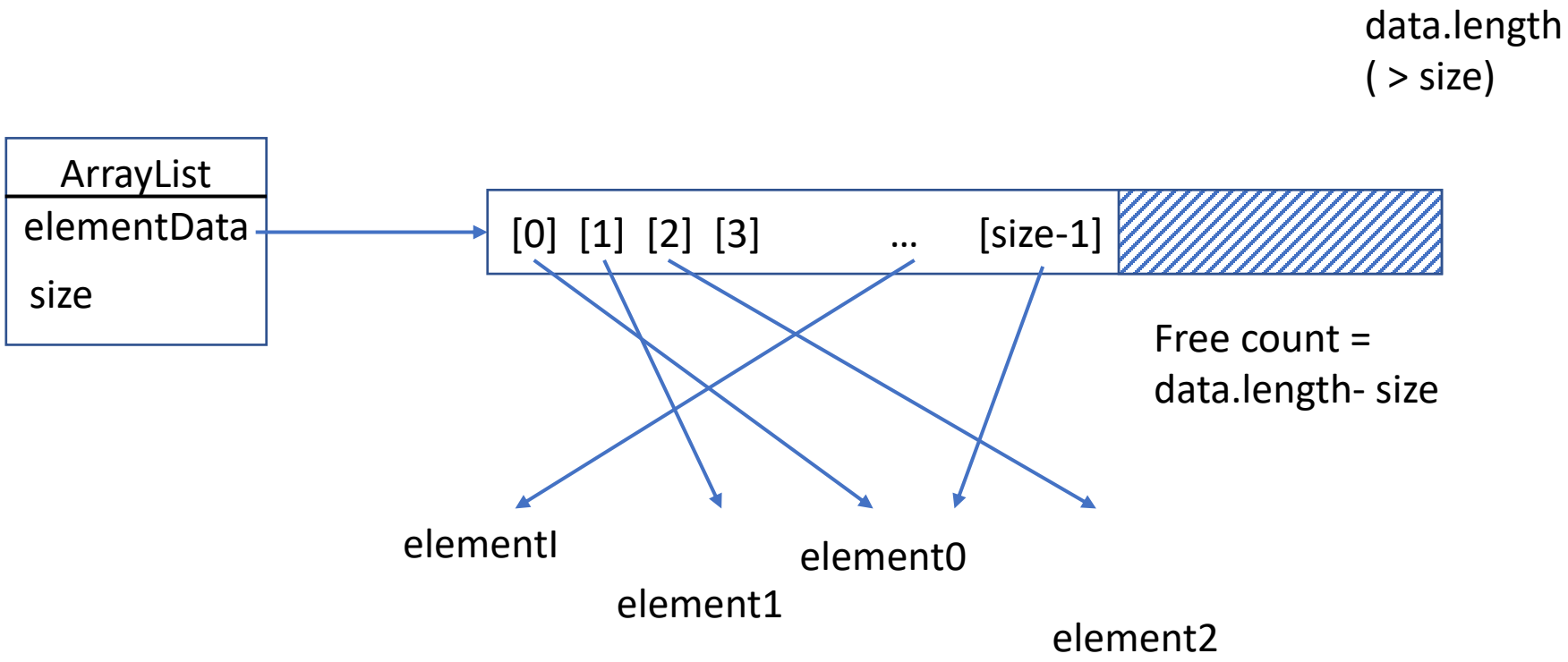
- ArrayList
  - add / indexOf / remove
  - resize
- LinkedList
- Arrays.sort, Tim Sort
- HashMap
  - hashCode, modulo or power 2, collisions
  - resize
  - Put, get, remove, iterate
- TreeMap
  - balanced tree, red-black tree
  - Put, get, remove, iterate
- PriorityQueue
  - Offer, poll

All with
Schemas
+ Algorithms
+ Associated Complexity
O(1), O(log N), O(N), O(N log N), O(n2)..

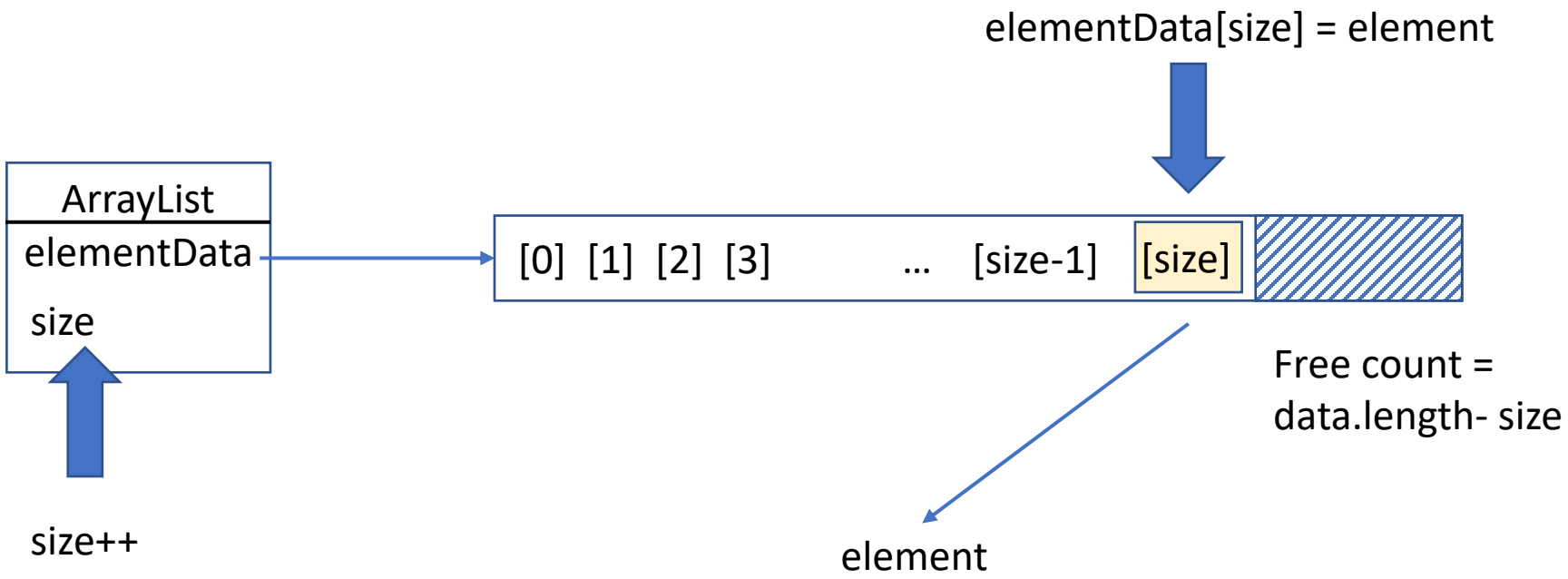
ArrayList<T>

ArrayList

```
    * The array buffer into which the elements of the ArrayList are stored.
   transient Object[] elementData; // non-private to simplify nested class access

    * The size of the ArrayList (the number of elements it contains).
   private int size;
```



ArrayList.add(element)
If Fast case : enough allocated length



Complexity = O(1) … 1 logical operation

Big O Notation

f(x) is O(g(x)) means: f(x) < M g(x) for x > x0 and M>0

Big *O* notation

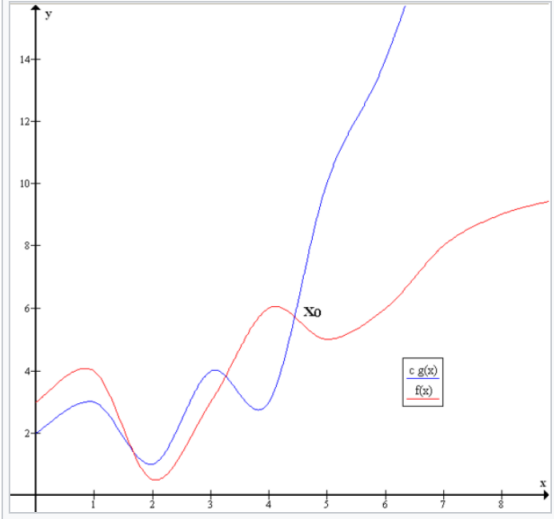
From Wikipedia, the free encyclopedia

Big *O* notation is a mathematical notation that describes the limiting behavior of a function when the argument tends towards a particular value or infinity. Big O is a member of a family of notations invented by Paul Bachmann,[1] Edmund Landau,[2] and others, collectively called **Bachmann–Landau notation** or **asymptotic notation**. The letter O was chosen by Bachmann to stand for *Ordnung*, meaning the order of approximation.

In computer science, big O notation is used to classify algorithms according to how their run time or space requirements grow as the input size grows.[3] In analytic number theory, big O notation is often used to express a bound on the difference between an arithmetical function and a better understood approximation; a famous example of such a difference is the remainder term in the prime number theorem. Big O notation is also used in many other fields to provide similar estimates.

Big O notation characterizes functions according to their growth rates: different functions with the same growth rate may be represented using the same O notation. The letter O is used because the growth rate of a function is also referred to as the **order of the function**. A description of a function in terms of big O notation usually only provides an upper bound on the growth rate of the function.

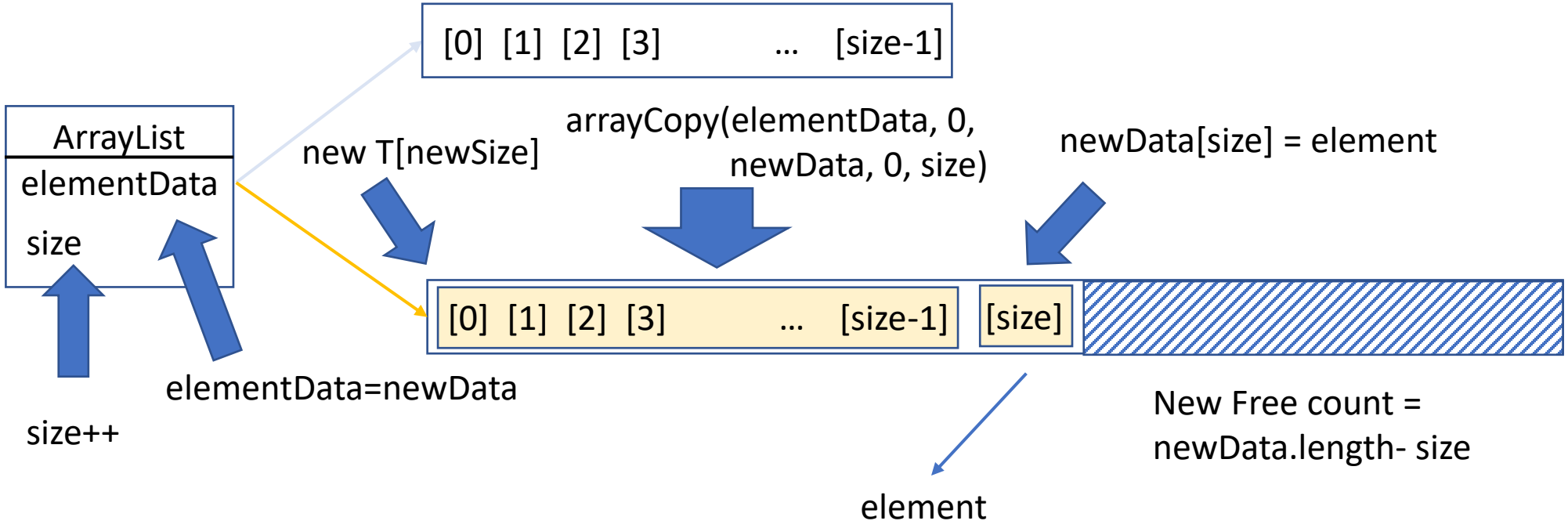
Associated with big O notation are several related notations, using the symbols o, Ω, ω, and Θ, to describe other kinds of bounds on asymptotic growth rates.



Example of Big O notation: $f(x) \in O(g(x))$ as there exists $M > 0$ (e.g., $M = 1$) and x_0 (e.g., $x_0 = 5$) such that $f(x) \leq Mg(x)$ whenever $x \geq x_0$.

Contents [hide]

ArrayList.add(element)
If Slow case : NOT enough allocated length



Complexity = O(size) … need copy all existing element pointers

How much to allocate in advance?

```
 * Increases the capacity to ensure that it can hold at least the
private void grow(int minCapacity) {
    // overflow-conscious code
    int oldCapacity = elementData.length;
    int newCapacity = oldCapacity + (oldCapacity >> 1);
    if (newCapacity - minCapacity < 0)
        newCapacity = minCapacity;
    if (newCapacity - MAX_ARRAY_SIZE > 0)
        newCapacity = hugeCapacity(minCapacity);
    // minCapacity is usually close to size, so this is a win:
    elementData = Arrays.copyOf(elementData, newCapacity);
}
```

compromize

+1 +2 +3 … +size/2 +… ???

Bad compromize:
Need copy every time adding

Bad compromize:
Lot of wasted memory if no more add

Memory preference

Compute preference

ArrayList initialCapacity : 0 .. then 10

```
 * Default initial capacity.
private static final int DEFAULT_CAPACITY = 10;

public ArrayList() {
    this.elementData = DEFAULTCAPACITY_EMPTY_ELEMENTDATA;
}

private static int calculateCapacity(Object[] elementData, int minCapacity) {
    if (elementData == DEFAULTCAPACITY_EMPTY_ELEMENTDATA) {
        return Math.max(DEFAULT_CAPACITY, minCapacity);
    }
    return minCapacity;
}
```

```
 * Constructs an empty list with the specified initial capacity.
public ArrayList(int initialCapacity) {
    if (initialCapacity > 0) {
        this.elementData = new Object[initialCapacity];
```

Use explicit if known size

Loop … add(element)
=> How many waste copies / times ?

```java
ArrayList<Object> ls = new ArrayList<>();
for(int i = 0; i < 1_000_000; i++) {
    ls.add(null);
}
// => count equivalent grows + copies
int countGrow = 0;
int totalCopy = 0;
for(int capacity = 10; capacity < 1_000_000; capacity = capacity + (capacity >> 1)) {
    countGrow++;
    totalCopy += capacity;
    System.out.println("[" + countGrow + "] " + capacity + " .. " + totalCopy);
}
```

Count	: 1	2	3	4	5	6		28	29
Capacity	: 10	15	22	33	49	73	….	540217	810325
Total Copies:	10	10+15= 25	25+22=47	80	129	202		1620647	2430972

Total : 2.4 Million copies
To add 1 Million values

Average Cost

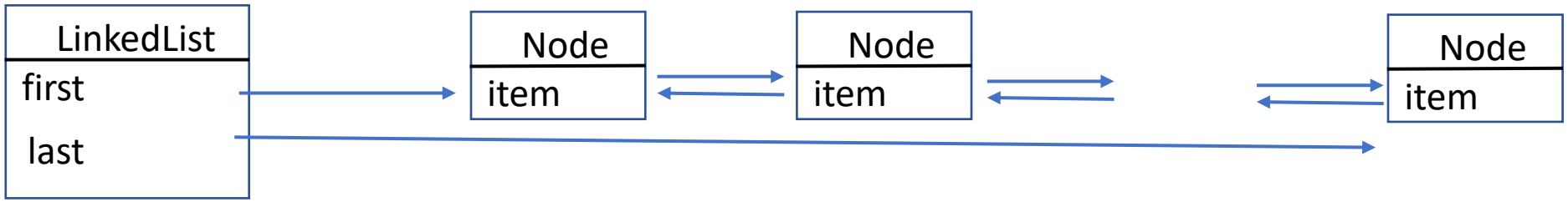
```
* <p>The <tt>size</tt>, <tt>isEmpty</tt>, <tt>get</tt>, <tt>set</tt>,
* <tt>iterator</tt>, and <tt>listIterator</tt> operations run in constant
* time.  The <tt>add</tt> operation runs in <i>amortized constant time</i>,
* that is, adding n elements requires O(n) time.  All of the other operations
* run in linear time (roughly speaking).  The constant factor is low compared
* to that for the <tt>LinkedList</tt> implementation.
```

Total copies = O(N) …. 2.4 * N for 1M

Number of reallocations: O(log N)

LinkedList … even worse !

```
* time.  The <tt>add</tt> operation runs in <i>amortized constant time</i>,
* that is, adding n elements requires O(n) time.  All of the other operations
* run in linear time (roughly speaking).  The constant factor is low compared
* to that for the <tt>LinkedList</tt> implementation.
```




```
 * Pointer to first node.
transient Node<E> first;

 * Pointer to last node.
transient Node<E> last;
```

```
private static class Node<E> {
    E item;
    Node<E> next;
    Node<E> prev;
```

Problem … « RAM » Random Access Memory … cache L1, L2

Typical access time :

RAM is ~100 nanos … 1000 x SLOWER than L1

But Typical capacity :

L1 is ~15 Ko … 1M x SMALLER than Ram (~100 Go)

Algorithm cost is driven by **Cache misses + Look Aheads**

ArrayList.indexOf(element)

```
 * Returns the index of the first occurrence of the specified element
public int indexOf(Object o) {
    if (o == null) {
        for (int i = 0; i < size; i++)
            if (elementData[i]==null)
                return i;
    } else {
        for (int i = 0; i < size; i++)
            if (o.equals(elementData[i]))
                return i;
    }
    return -1;
}
```

Average Cost indexOf()

Positive find => … return break loop maybe at position 1, or 2, … or N

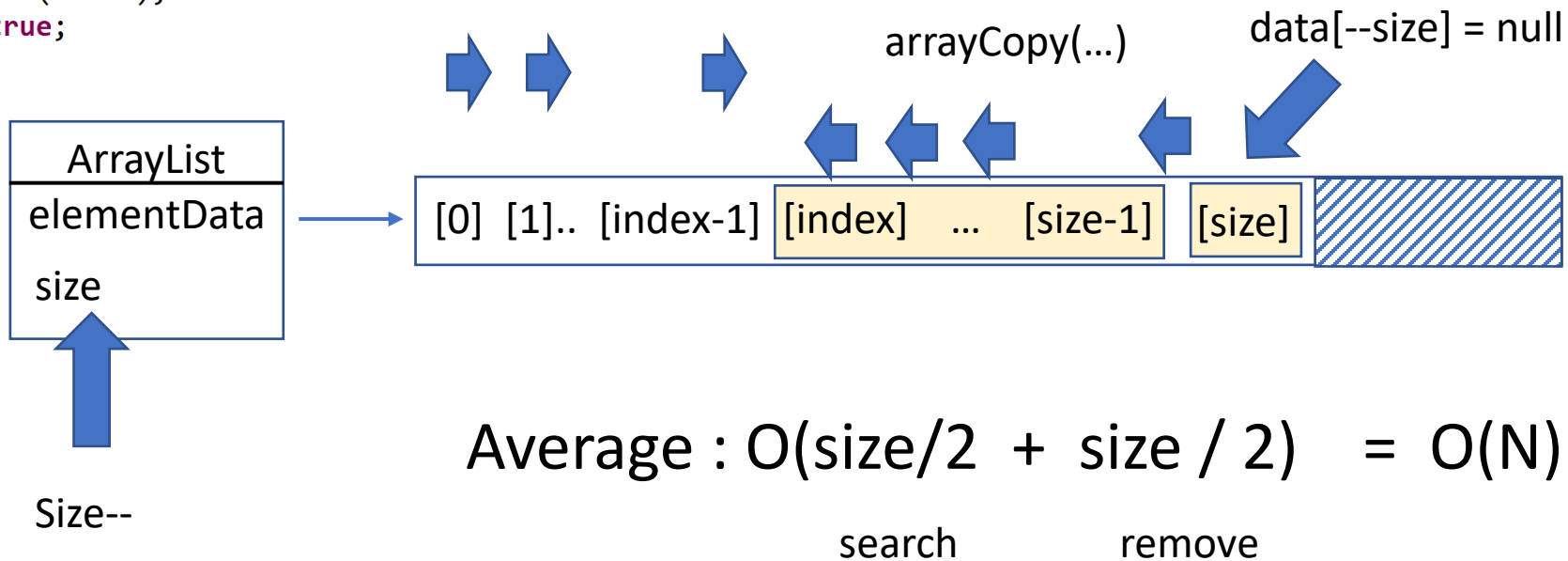
$$\frac{1+2+3+\ \ldots\ +N}{N} = \frac{(N+1) * N}{2N} = \frac{N+1}{2}$$ = half scan in average

Negative find => … always full scan = N

ArrayList.remove(element) = indexOf + fastRemove by index

```java
 * Removes the first occurrence of the specified element from this list,
public boolean remove(Object o) {
    if (o == null) {
        for (int index = 0; index < size; index++)
            if (elementData[index] == null) {
                fastRemove(index);
                return true;
            }
    } else {
        for (int index = 0; index < size; index++)
            if (o.equals(elementData[index])) {
                fastRemove(index);
                return true;
            }
    }
    return false;
}
```

```java
private void fastRemove(int index) {
    modCount++;
    int numMoved = size - index - 1;
    if (numMoved > 0)
        System.arraycopy(elementData, index+1, elementData, index,
                         numMoved);
    elementData[--size] = null; // clear to let GC do its work
}
```

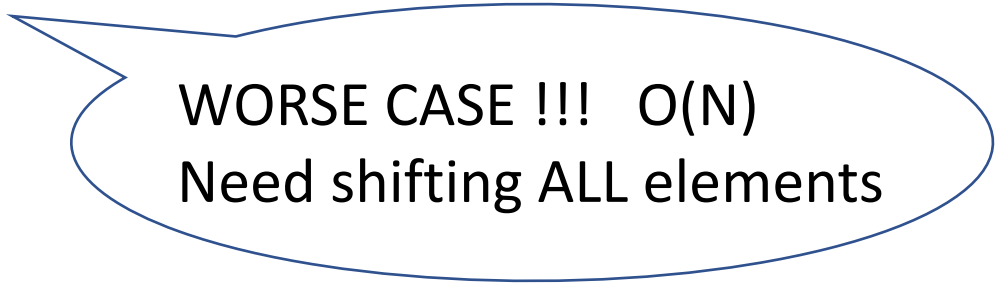


Average : O(size/2 + size / 2) = O(N)

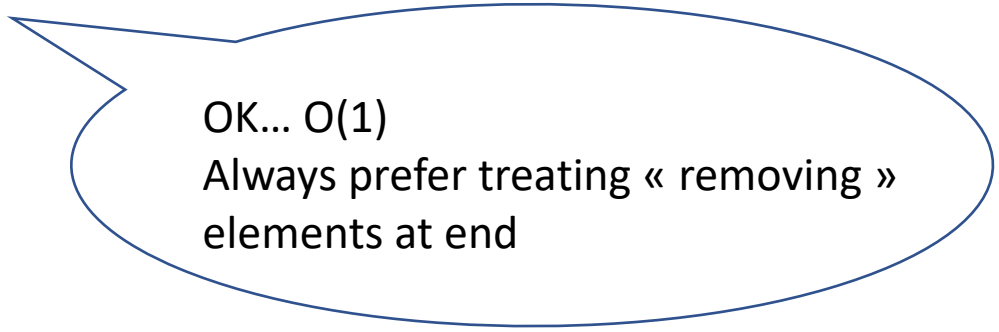
search remove

ArrayList.remove(index)

list.remove(0)



list.remove(list.size()- 1)



HashMap<K,V>

HashMap<K,V>

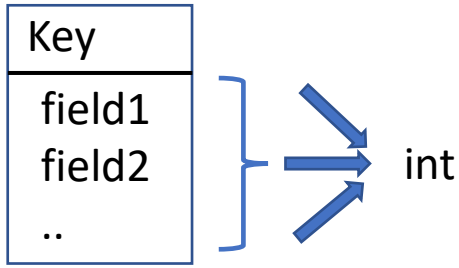
```
 * The table, initialized on first use, and resized as
transient Node<K,V>[] table;

 * Holds cached entrySet(). Note that AbstractMap fields are used
transient Set<Map.Entry<K,V>> entrySet;

 * The number of key-value mappings contained in this map.
transient int size;

 * The number of times this HashMap has been structurally modified
transient int modCount;

 * The next size value at which to resize (capacity * load factor).
// (The javadoc description is true upon serialization.
// Additionally, if the table array has not been allocated, this
// field holds the initial array capacity, or zero signifying
// DEFAULT_INITIAL_CAPACITY.)
int threshold;

 * The load factor for the hash table.
final float loadFactor;
```

```
/**
 * Basic hash bin node, used for most entries.  (See below for
 * TreeNode subclass, and in LinkedHashMap for its Entry subclass.)
 */
static class Node<K,V> implements Map.Entry<K,V> {
    final int hash;
    final K key;
    V value;
    Node<K,V> next;
```

… LinkedHashMap<K,V>

```
 * HashMap.Node subclass for normal LinkedHashMap entries.
static class Entry<K,V> extends HashMap.Node<K,V> {
    Entry<K,V> before, after;
```

hashCode()
injective function for Key -> int



Mix all bits information
Example using « ^ » (xor) :
int x,int y => x ^ y
long value => (value ^ (value>>>32))
Example using prime: x*31+y

Expected properties:

1/ repeatable (same object => same result .. No time or address dependent)

2/ when key1.equals(key2) => same hashCode

3/ when different key => expect BUT NOT mandatory to have different hashCode

4/ use all bits information on key (no naive return 123, even if legal)

5/ try to reach all possible values of « int » range: [-2^31… +2^31]

Hashing Function, then Modulo « % » or Bitwise « & »

```
 * Computes key.hashCode() and spreads (XORs) higher bits of hash
static final int hash(Object key) {
    int h;
    return (key == null) ? 0 : (h = key.hashCode()) ^ (h >>> 16);
}
```

```
final Node<K,V> getNode(int hash, Object key) {
    Node<K,V>[] tab; Node<K,V> first, e; int n; K k;
    if ((tab = table) != null && (n = tab.length) > 0 &&
        (first = tab[(n - 1) & hash]) != null) {
```

.. Mostly equivalent to « modulo »

hash = Key.hashCode()

… « int » in range [-2^31, +2^31]

hash2 = Math.abs(hash)

… in [0, +2^31] .. Lost 1 bit

index = hash2 % M

Randomly distributed when M is Prime

… in range [0, size-1]

OK to lookup in array « table[size] »

Jdk .. Use capacity=2^power

```
/**
 * The default initial capacity - MUST be a power of two.
 */
static final int DEFAULT_INITIAL_CAPACITY = 1 << 4; // aka 16
```

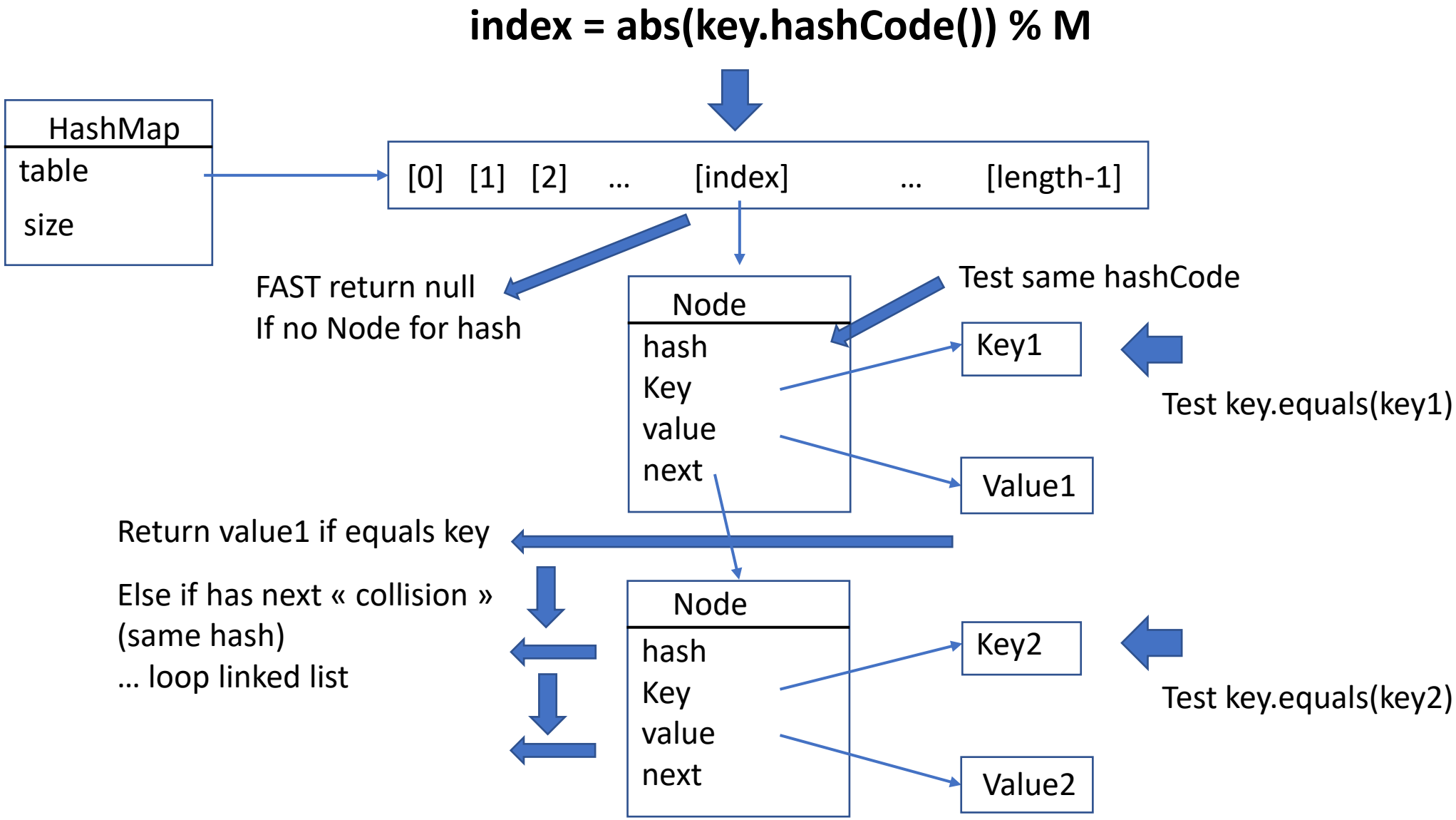
Hash to index .. using « **hash & (n-1)** »

Example:	(in base 2)
N =32 = (1 << 5) =	0 0 0 1 0 0 0 0 0
n-1 = 31 =	0 0 0 0 1 1 1 1 1
Hash =	y y y y x x x x x
Hash&(n-1)=	0 0 0 0 x x x x x

Resize: capacity *2 .. using « **capacity << 1** »
(jdk : no decrease capacity)

Re-hash after resize => index change to index or index*2

hashCode()
… lookup index for finding value by key if present



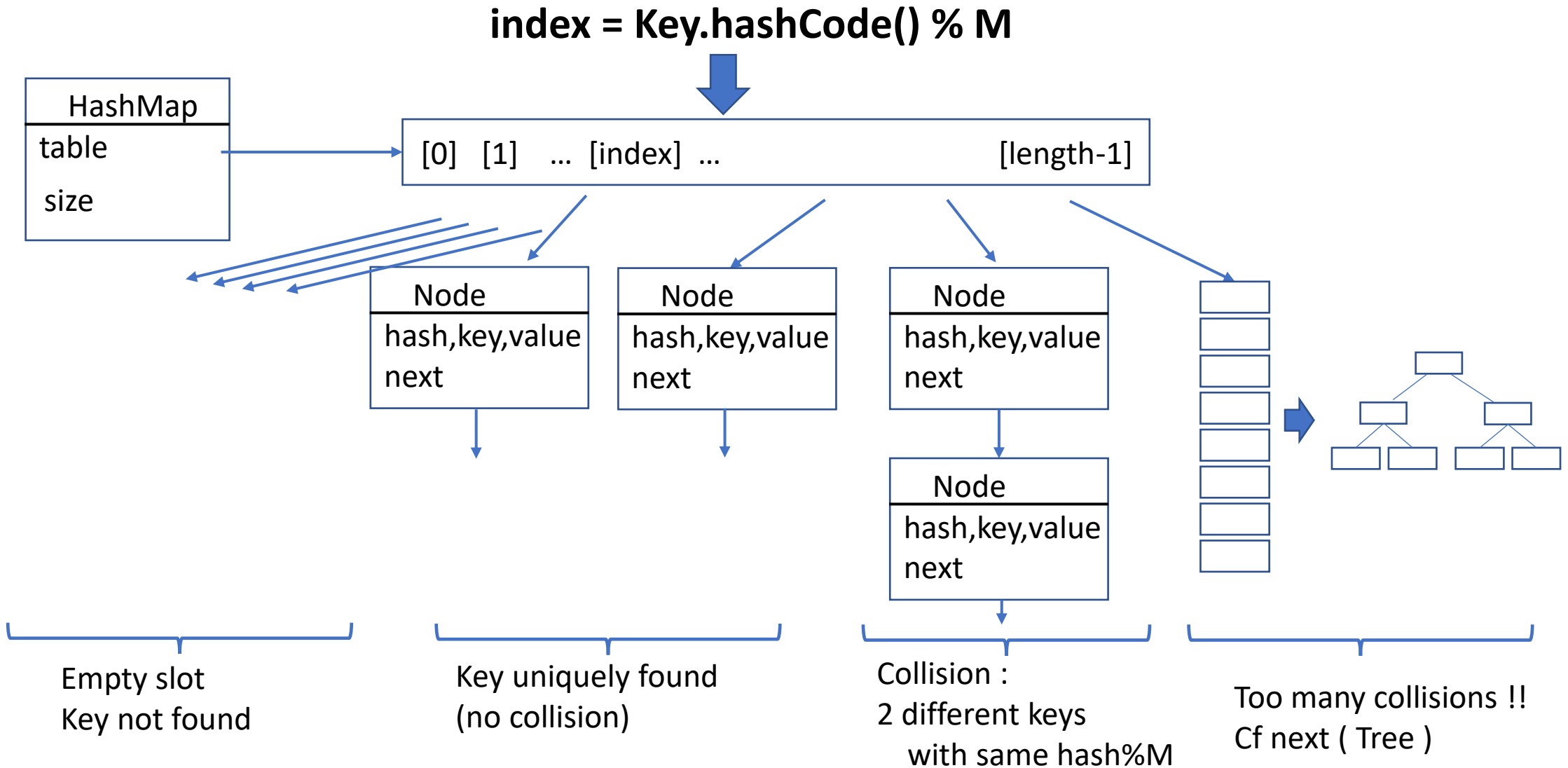
Strategy to Reduce Collisions Occurrences

1/ use « GOOD » hashCode() function …. With hopefully equally distributed values

2/ use « BIG » M allocated tables length (example: M > 2 * N)
… wasting memory, but improving selectivity (avoid %M collisions)

3/ if using « hashCode % M » … prefer M as Prime number
(NOT the implementation of jdk)

Same « hashCode()%M » : collisions



LinkedList to Tree … >= 8

```
/**
 * The bin count threshold for using a tree rather than list for a
 * bin.  Bins are converted to trees when adding an element to a
 * bin with at least this many nodes. The value must be greater
 * than 2 and should be at least 8 to mesh with assumptions in
 * tree removal about conversion back to plain bins upon
 * shrinkage.
 */
static final int TREEIFY_THRESHOLD = 8;
```

HashMap.get(key) … O(1)

Fast path
O(1) …no collision

many collisions
O(log(C)) …

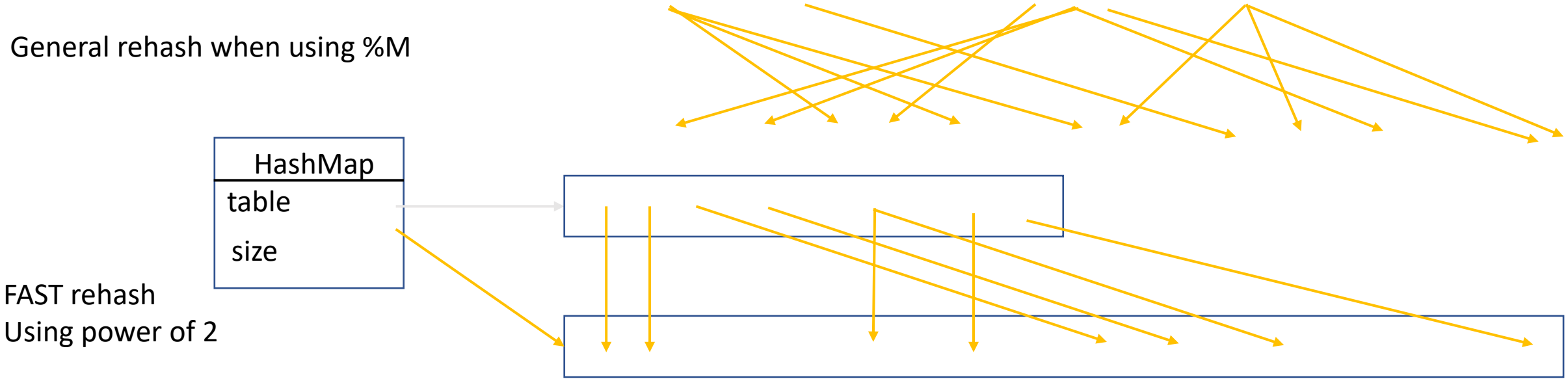
medium path
O(8/2) …few collision(s)

```
 * Returns the value to which the specified key is mapped,
public V get(Object key) {
    Node<K,V> e;
    return (e = getNode(hash(key), key)) == null ? null : e.value;
}

 * Implements Map.get and related methods.
final Node<K,V> getNode(int hash, Object key) {
    Node<K,V>[] tab; Node<K,V> first, e; int n; K k;
    if ((tab = table) != null && (n = tab.length) > 0 &&
        (first = tab[(n - 1) & hash]) != null) {
        if (first.hash == hash && // always check first node
            ((k = first.key) == key || (key != null && key.equals(k))))
            return first;
        if ((e = first.next) != null) {
            if (first instanceof TreeNode)
                return ((TreeNode<K,V>)first).getTreeNode(hash, key);
            do {
                if (e.hash == hash &&
                    ((k = e.key) == key || (key != null && key.equals(k))))
                    return e;
            } while ((e = e.next) != null);
        }
    }
    return null;
}
```

HashMap.put() … may resize

Hash size « M » should be adapted to number of element « N »
greater (but not too much)

.. Sometime re-copy all ! … reduce collisions



Rehash is FAST … (not recomputed, and index unchanged OR *2)

HashMap.resize(): ?>threshold and capacity*2

```
    if (++size > threshold)
        resize();
    afterNodeInsertion(evict);
    return null;
}

 * Initializes or doubles table size.  If null, allocates in
final Node<K,V>[] resize() {
    Node<K,V>[] oldTab = table;
    int oldCap = (oldTab == null) ? 0 : oldTab.length;
    int oldThr = threshold;
    int newCap, newThr = 0;
    if (oldCap > 0) {
        if (oldCap >= MAXIMUM_CAPACITY) {
            threshold = Integer.MAX_VALUE;
            return oldTab;
        }
        else if ((newCap = oldCap << 1) < MAXIMUM_CAPACITY &&
                 oldCap >= DEFAULT_INITIAL_CAPACITY)
            newThr = oldThr << 1; // double threshold
    }
    else if (oldThr > 0) // initial capacity was placed in threshold
        newCap = oldThr;
    else {               // zero initial threshold signifies using defaults
        newCap = DEFAULT_INITIAL_CAPACITY;
        newThr = (int)(DEFAULT_LOAD_FACTOR * DEFAULT_INITIAL_CAPACITY);
    }
    if (newThr == 0) {
        float ft = (float)newCap * loadFactor;
        newThr = (newCap < MAXIMUM_CAPACITY && ft < (float)MAXIMUM_CAPACITY ?
                  (int)ft : Integer.MAX_VALUE);
    }
```

May resize after put()

capacity*2, threshold*2

Init : capacity=16,
loadFactor=0.75
..threshold=12

Loop put(k,v) … how many resize() + total Re-hashes?

```java
HashMap<Integer,Integer> map = new HashMap<>();
for(int i = 0; i < 1_000_000; i++) {
    map.put(i, null);
}
// => count equivalent grows + rehashes
int capacity = 16;
int threshold = (int) (capacity * 0.75);
System.out.println("init " + capacity + ", threshold:" + threshold);
int countGrow = 0;
int totalRehash = 0;
for(; capacity < 1_000_000;) {
    countGrow++;
    totalRehash += threshold;
    capacity = capacity << 1;
    threshold = threshold << 1;
    System.out.println("[" + countGrow + "] " + capacity
            + ", " + threshold + " .. " + totalRehash);
}
```

```
init 16, threshold:12
[1] 32, 24 .. 12
[2] 64, 48 .. 36
[3] 128, 96 .. 84
[4] 256, 192 .. 180
[5] 512, 384 .. 372
[6] 1024, 768 .. 756
[7] 2048, 1536 .. 1524
[8] 4096, 3072 .. 3060
[9] 8192, 6144 .. 6132
[10] 16384, 12288 .. 12276
[11] 32768, 24576 .. 24564
[12] 65536, 49152 .. 49140
[13] 131072, 98304 .. 98292
[14] 262144, 196608 .. 196596
[15] 524288, 393216 .. 393204
[16] 1048576, 786432 .. 786420
```

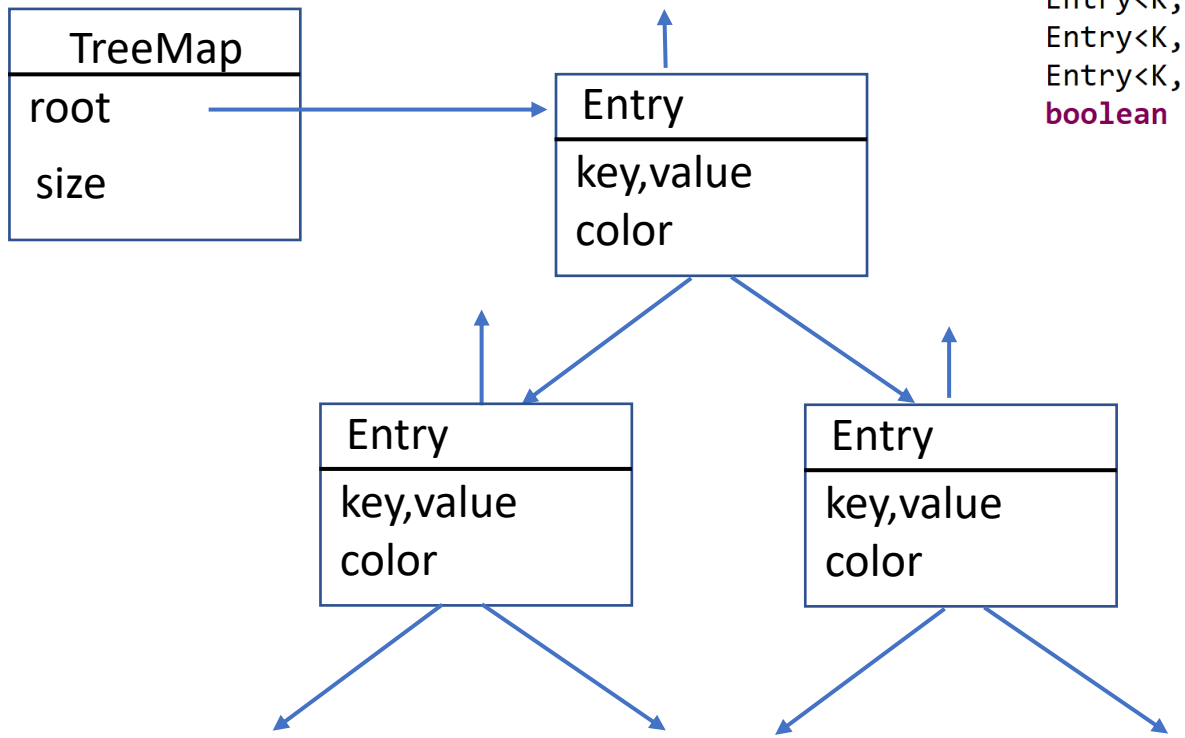
Put 1 Million values => 16 resizes … 700k total rehashes

~ 0.8 N … O(N)

TreeMap<K,V>

TreeMap<K,V>

```
private transient Entry<K,V> root;

 * The number of entries in the tree
private transient int size = 0;

 * The number of structural modifications to the tree.
private transient int modCount = 0;
```



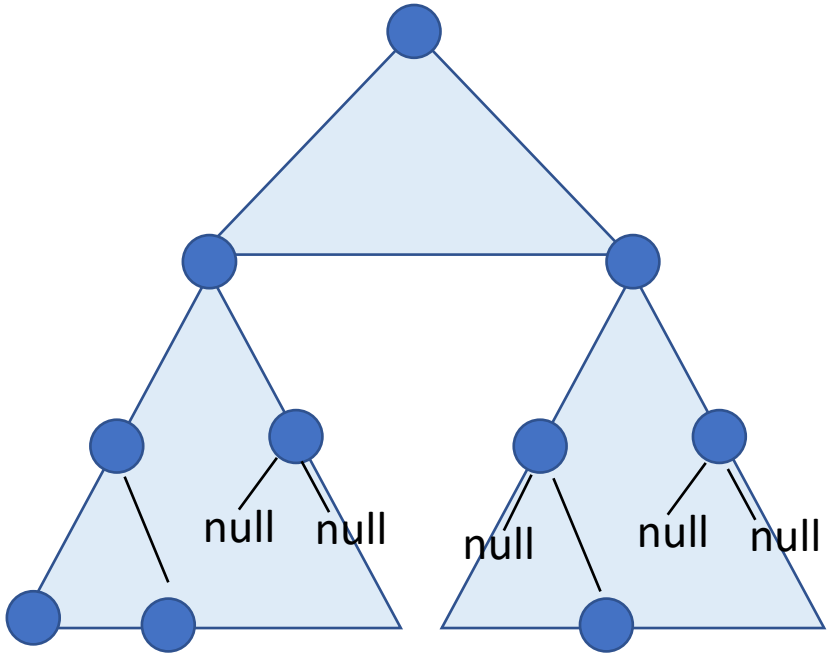

```
// Red-black mechanics

private static final boolean RED   = false;
private static final boolean BLACK = true;

 * Node in the Tree.  Doubles as a means to pass key-value pairs back to

static final class Entry<K,V> implements Map.Entry<K,V> {
    K key;
    V value;
    Entry<K,V> left;
    Entry<K,V> right;
    Entry<K,V> parent;
    boolean color = BLACK;
```

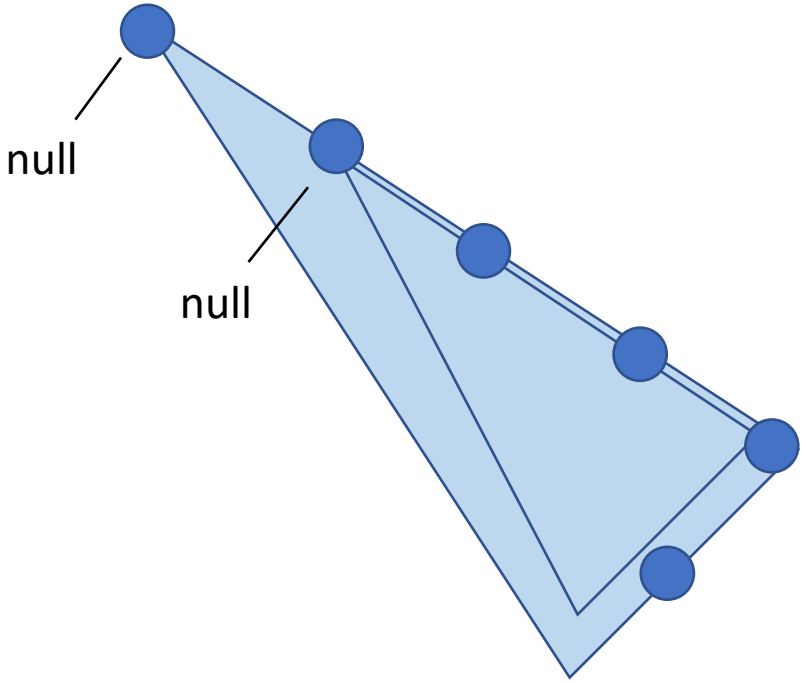
Balanced / Un-balanced Trees

tree depth
= O(log N)

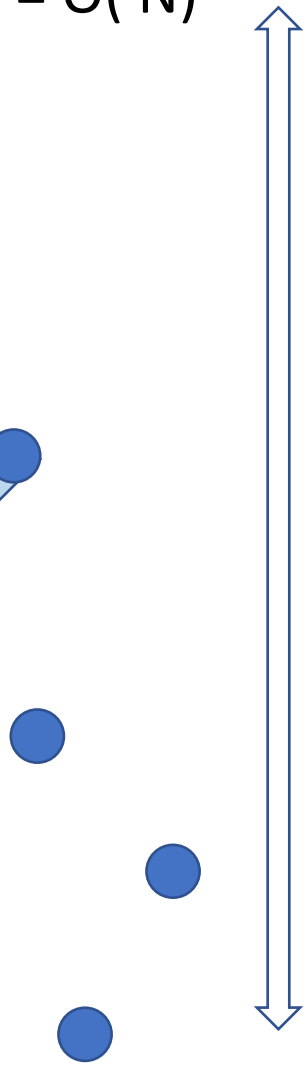
intermediate
levels:
Hopefully
Entierly filled

leaf levels
may be empty
(not multiple of 2^N)





tree depth
= O(N)



Weight Left SubTree ~= Weight Right Sub Tree

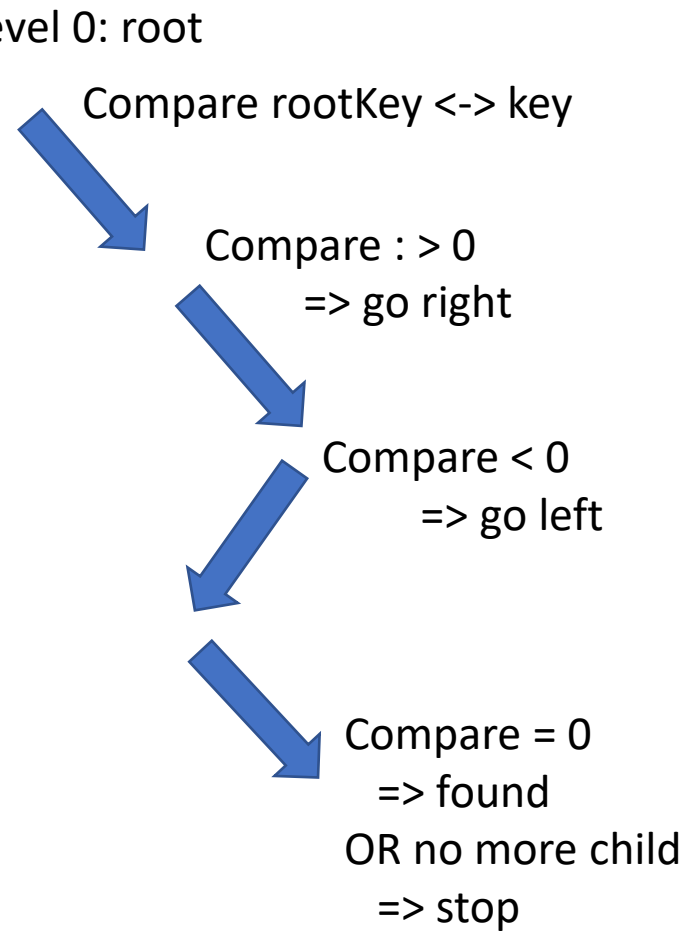
All path = depth-1 or depth

TreeMap.get(key)

```
 * Returns this map's entry for the given key, or {@code null} if the map
final Entry<K,V> getEntry(Object key) {
    // Offload comparator-based version for sake of performance
    if (comparator != null)
        return getEntryUsingComparator(key);
    if (key == null)
        throw new NullPointerException();
    @SuppressWarnings("unchecked")
        Comparable<? super K> k = (Comparable<? super K>) key;
    Entry<K,V> p = root;
    while (p != null) {
        int cmp = k.compareTo(p.key);
        if (cmp < 0)
            p = p.left;
        else if (cmp > 0)
            p = p.right;
        else
            return p;
    }
    return null;
}
```

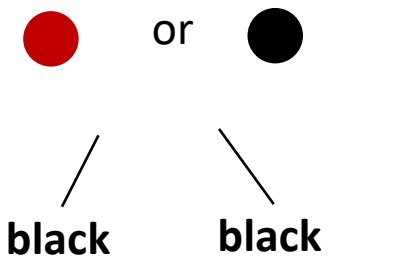
Max operations
= tree depth
= O(log N)

N=2^depth



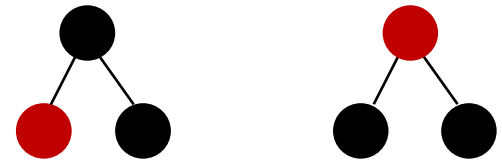
Red-Black Rules

1 Every node is either red or black.

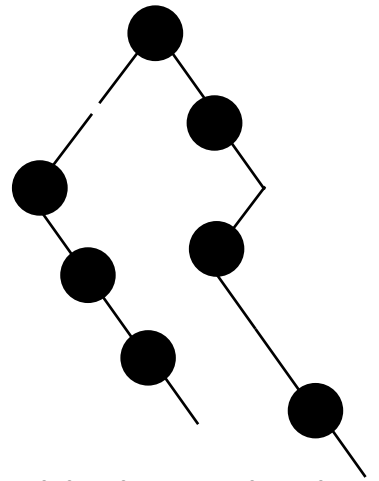


2 All NIL nodes (figure 1) are considered black.

3 A red node does not have a red child.



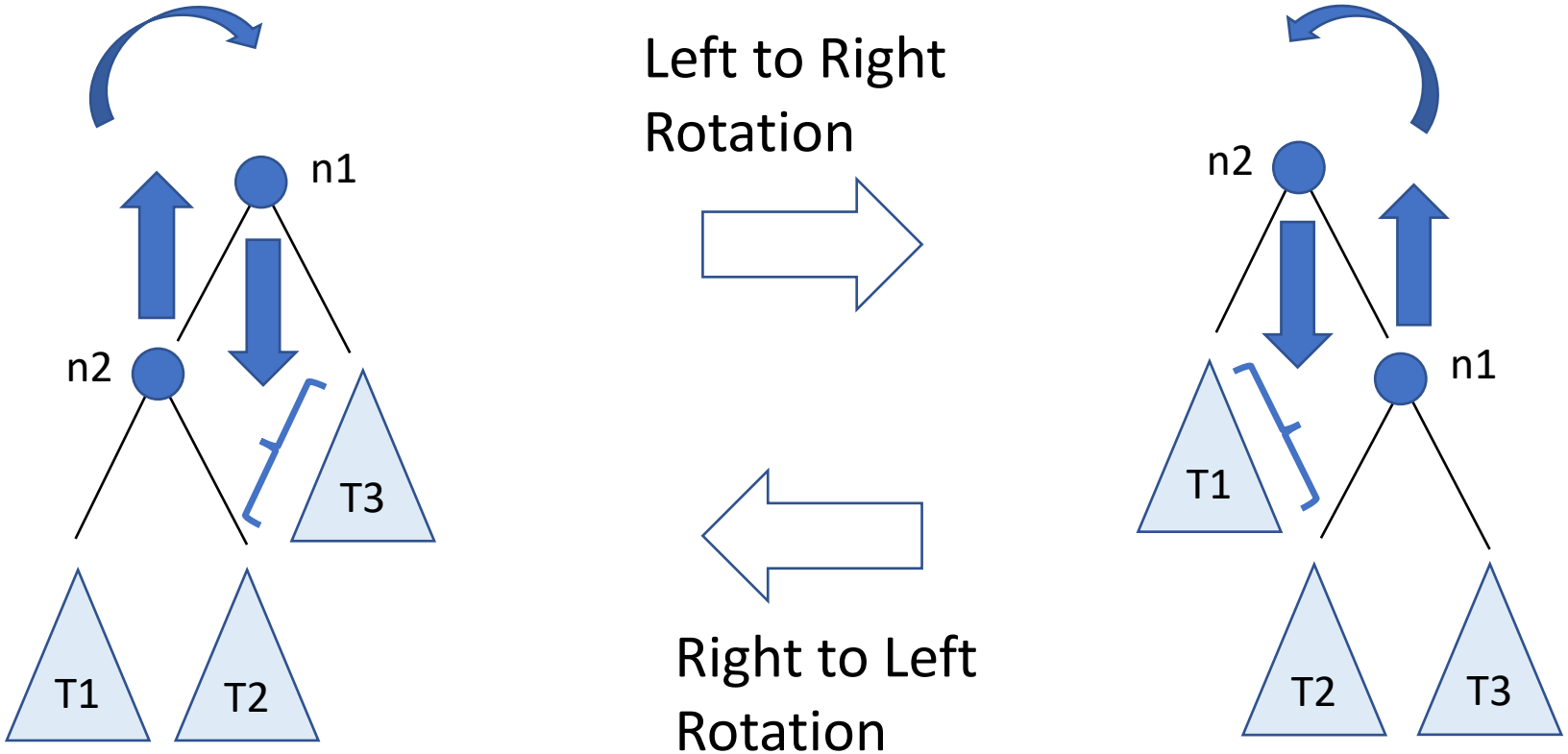
4 Every path from a given node to any of its descendant NIL nodes goes through the same number of black nodes.



=> the path from the root to the farthest leaf is no more than twice as long as the path from the root to the nearest leaf

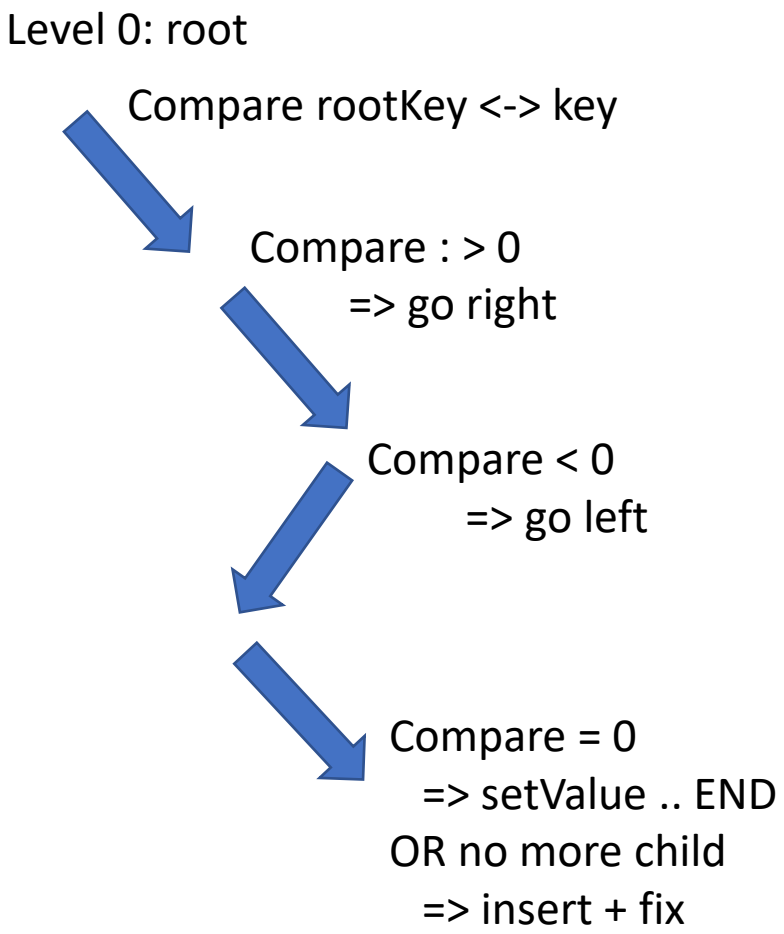
n1 black = n2 back

Rotations


n1
n2
T1
T2
T3
Left to Right Rotation
Right to Left Rotation
n2
n1
T1
T2
T3

TreeMap.put(key, value) .. [1/2] find down insert point

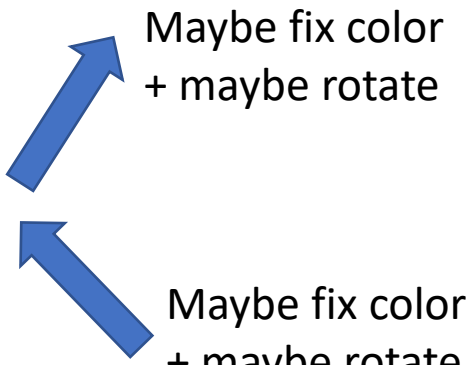
```
 * Associates the specified value with the specified key in this map.
public V put(K key, V value) {
    Entry<K,V> t = root;

        .....

    else {
        if (key == null)
            throw new NullPointerException();
        @SuppressWarnings("unchecked")
            Comparable<? super K> k = (Comparable<? super K>) key;
        do {
            parent = t;
            cmp = k.compareTo(t.key);
            if (cmp < 0)
                t = t.left;
            else if (cmp > 0)
                t = t.right;
            else
                return t.setValue(value);
        } while (t != null);
    }
    Entry<K,V> e = new Entry<>(key, value, parent);
    if (cmp < 0)
        parent.left = e;
    else
        parent.right = e;
    fixAfterInsertion(e);
    size++;
    modCount++;
    return null;
```



TreeMap.put(key, value) .. [2/2] fix up color+rotate

```
private void fixAfterInsertion(Entry<K,V> x) {
    x.color = RED;

    while (x != null && x != root && x.parent.color == RED) {
        if (parentOf(x) == leftOf(parentOf(parentOf(x)))) {
            Entry<K,V> y = rightOf(parentOf(parentOf(x)));
            if (colorOf(y) == RED) {
                setColor(parentOf(x), BLACK);
                setColor(y, BLACK);
                setColor(parentOf(parentOf(x)), RED);
                x = parentOf(parentOf(x));
            } else {
                if (x == rightOf(parentOf(x))) {
                    x = parentOf(x);
                    rotateLeft(x);
                }
                setColor(parentOf(x), BLACK);
                setColor(parentOf(parentOf(x)), RED);
                rotateRight(parentOf(parentOf(x)));
            }
        } else {
            Entry<K,V> y = leftOf(parentOf(parentOf(x)));
            if (colorOf(y) == RED) {
                setColor(parentOf(x), BLACK);
                setColor(y, BLACK);
                setColor(parentOf(parentOf(x)), RED);
                x = parentOf(parentOf(x));
            } else {
                if (x == leftOf(parentOf(x))) {
                    x = parentOf(x);
                    rotateRight(x);
                }
                setColor(parentOf(x), BLACK);
                setColor(parentOf(parentOf(x)), RED);
                rotateLeft(parentOf(parentOf(x)));
            }
        }
    }
    root.color = BLACK;
}
```

Finished on black parent node (or root)



Time cost … O(log N)

```
* <p>This implementation provides guaranteed log(n) time cost for the
* {@code containsKey}, {@code get}, {@code put} and {@code remove}
* operations.  Algorithms are adaptations of those in Cormen, Leiserson, and
* Rivest's <em>Introduction to Algorithms</em>.
```

.get(key)
.containsKey(key)

} Read-only

.put(key, value)
.remove(key)

} Unitary write
Idempotent
(not atomic, need synchronize)

.put() and .remove() slightly slower than get
: need fixup .. But still very fast

TreeMap.iterator / subMap / headMap / tailMap

```
 * Returns the successor of the specified Entry, or null if no such.
static <K,V> TreeMap.Entry<K,V> successor(Entry<K,V> t) {
    if (t == null)
        return null;
    else if (t.right != null) {
        Entry<K,V> p = t.right;
        while (p.left != null)
            p = p.left;
        return p;
    } else {
        Entry<K,V> p = t.parent;
        Entry<K,V> ch = t;
        while (p != null && ch == p.right) {
            ch = p;
            p = p.parent;
        }
        return p;
    }
}
```

```
 * Returns the predecessor of the specified Entry, or null if no such.
static <K,V> Entry<K,V> predecessor(Entry<K,V> t) {
    if (t == null)
        return null;
    else if (t.left != null) {
        Entry<K,V> p = t.left;
        while (p.right != null)
            p = p.right;
        return p;
    } else {
        Entry<K,V> p = t.parent;
        Entry<K,V> ch = t;
        while (p != null && ch == p.left) {
            ch = p;
            p = p.parent;
        }
        return p;
    }
}
```

Unitary successor() and predecessor() run in O(log N)

… scanning all TreeMap runs in O(N log N)
not optimal compared to Arrays.sort() + scanning in ArrayList

Arrays.sort()

Arrays.sort() … O(N log N)

Many algorithms

Buble Sort (..bad O(N^2)) / Insert Sort / Quick Sort / Merge Sort … not used in java

ParallelSort .. => using common ForkJoinPool + Dual Pivot Quick Sort

Dual Pivot Quick Sort (called from Arrays.sort() … on primitive types)

Tim Sort … default in ArrayList and Arrays.sort(.. Comparator)

```
 * Sorts the specified range of the specified array of objects according
public static <T> void sort(T[] a, int fromIndex, int toIndex,
                            Comparator<? super T> c) {
    if (c == null) {
        sort(a, fromIndex, toIndex);
    } else {
        rangeCheck(a.length, fromIndex, toIndex);
        if (LegacyMergeSort.userRequested)
            legacyMergeSort(a, fromIndex, toIndex, c);
        else
            TimSort.sort(a, fromIndex, toIndex, c, null, 0, 0);
    }
}
```

```
 * Sorts the specified array into ascending numerical order.
public static void sort(int[] a) {
    DualPivotQuicksort.sort(a, 0, a.length - 1, null, 0, 0);
}
```

Tim Peter’s Sort

```
/**
 * A stable, adaptive, iterative mergesort that requires far fewer than
 * n lg(n) comparisons when running on partially sorted arrays, while
 * offering performance comparable to a traditional mergesort when run
 * on random arrays.  Like all proper mergesorts, this sort is stable and
 * runs O(n log n) time (worst case).  In the worst case, this sort requires
 * temporary storage space for n/2 object references; in the best case,
 * it requires only a small constant amount of space.
 *
 * This implementation was adapted from Tim Peters's list sort for
 * Python, which is described in detail here:
 *
 *   http://svn.python.org/projects/python/trunk/Objects/listsort.txt
```

PriorityQueue<T>

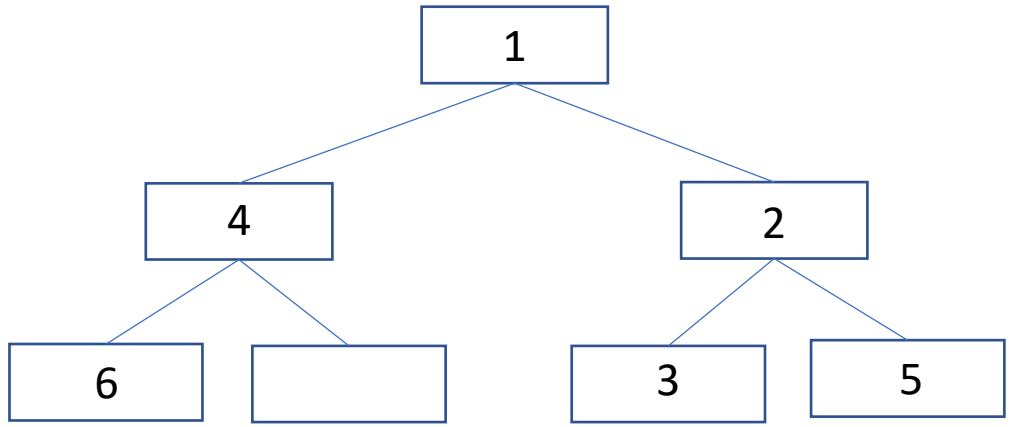
PriorityQueue Property:
for all node, parent value <= child value

Compared to TreeMap … no constraint between left child and right child

Root contains the min value

… all others looks « unordered »

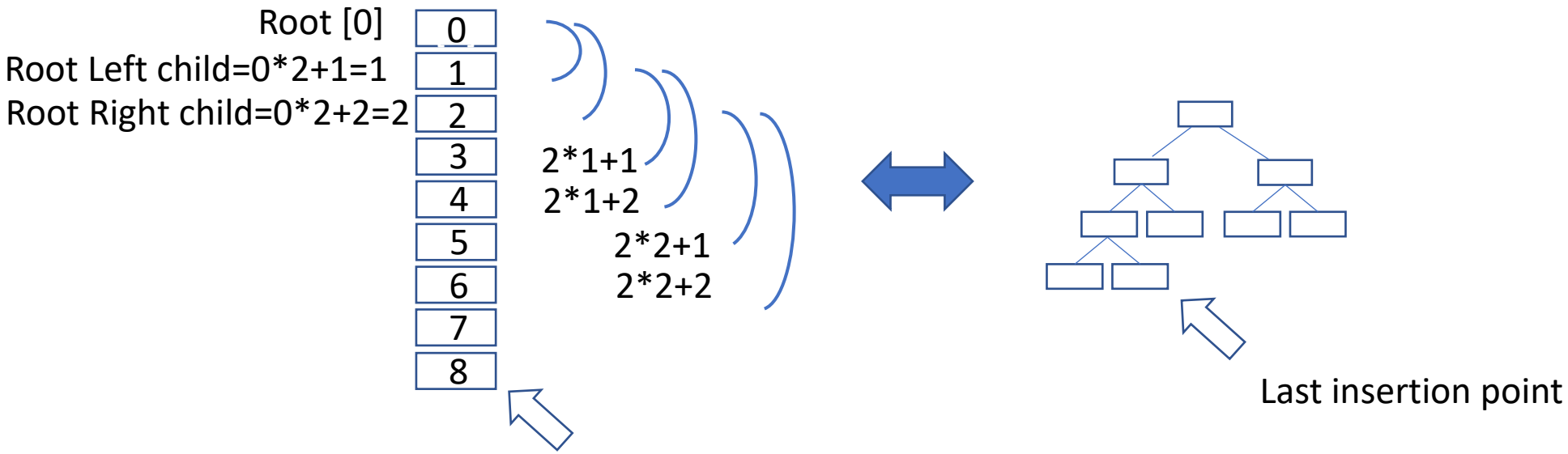
Example for
1, 2, 3, 4, 5, 6



PriorityQueue … Balanced Binary Heap as Array

```
/**
 * Priority queue represented as a balanced binary heap: the two
 * children of queue[n] are queue[2*n+1] and queue[2*(n+1)].  The
 * priority queue is ordered by comparator, or by the elements'
 * natural ordering, if comparator is null: For each node n in the
 * heap and each descendant d of n, n <= d.  The element with the
 * lowest value is in queue[0], assuming the queue is nonempty.
 */
transient Object[] queue; // non-private to simplify nested class access

 * The number of elements in the priority queue.
private int size = 0;
```

Tree as Array



Fast arithmetic base 2:

« i *2 » : i << 1

« i /2 » : i >>> 1

PriorityQueue.peek() … O(1)

peek() : return but do not consume (no remove) min value
… simply look at root !

```
public E peek() {
    return (size == 0) ? null : (E) queue[0];
}
```

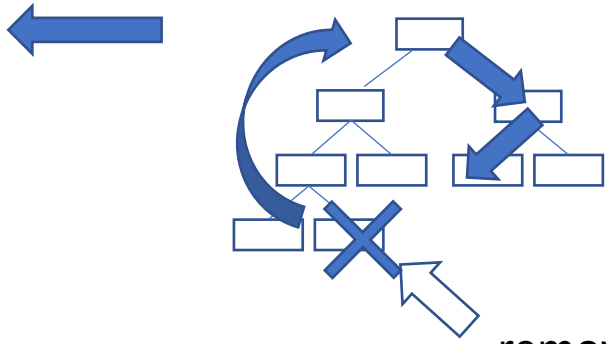
PriorityQueue.poll() … O(log N)

```java
public E poll() {
    if (size == 0)
        return null;
    int s = --size;
    modCount++;
    E result = (E) queue[0];
    E x = (E) queue[s];
    queue[s] = null;
    if (s != 0)
        siftDown(0, x);
    return result;
}
```

```java
/**
 * Inserts item x at position k, maintaining heap invariant by
 * demoting x down the tree repeatedly until it is less than or
 * equal to its children or is a leaf.
 */
private void siftDown(int k, E x) {
    if (comparator != null)
        siftDownUsingComparator(k, x);
    else
        siftDownComparable(k, x);
}
```

```java
private void siftDownUsingComparator(int k, E x) {
    int half = size >>> 1;
    while (k < half) {
        int child = (k << 1) + 1;
        Object c = queue[child];
        int right = child + 1;
        if (right < size &&
            comparator.compare((E) c, (E) queue[right]) > 0)
            c = queue[child = right];
        if (comparator.compare(x, (E) c) <= 0)
            break;
        queue[k] = c;
        k = child;
    }
    queue[k] = x;
}
```

Poll root



Fix order
Down until ok
Compare to child right,
then child left

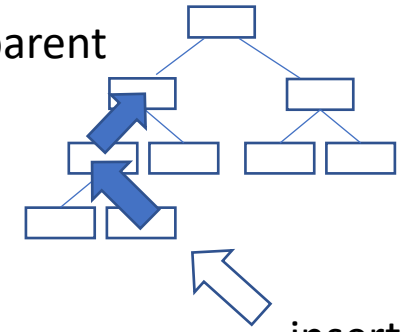
remove last,
put at root

PriorityQueue.add(v) / .offer(v) … O(log N)

```java
 * Inserts the specified element into this priority queue.
public boolean offer(E e) {
    if (e == null)
        throw new NullPointerException();
    modCount++;
    int i = size;
    if (i >= queue.length)
        grow(i + 1);
    size = i + 1;
    if (i == 0)
        queue[0] = e;
    else
        siftUp(i, e);
    return true;
}
```

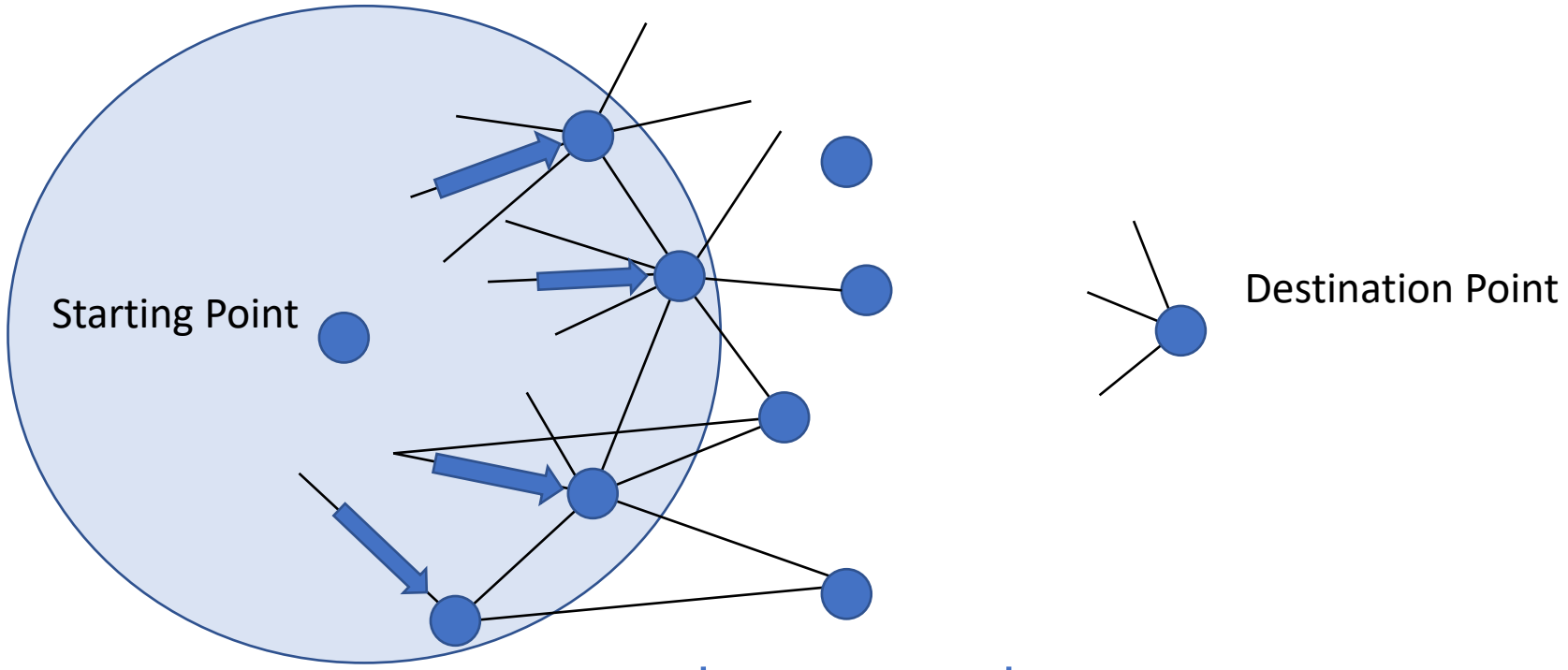
```java
private void siftUpComparable(int k, E x) {
    Comparable<? super E> key = (Comparable<? super E>) x;
    while (k > 0) {
        int parent = (k - 1) >>> 1;
        Object e = queue[parent];
        if (key.compareTo((E) e) >= 0)
            break;
        queue[k] = e;
        k = parent;
    }
    queue[k] = key;
}
```

Loop Swap parent until lower



insert last

Typical PriorityQueue Usages … Shortest Path Finding



Shortest Path Finding Algorithms
Bellman-Ford, Dijkstra, ..

```
procedure Shortest-Path-Faster-Algorithm(G, s)
 1    for each vertex v ≠ s in V(G)
 2        d(v) := ∞
 3    d(s) := 0
 4    push s into Q
 5    while Q is not empty do
 6        u := poll Q
 7        for each edge (u, v) in E(G) do
 8            if d(u) + w(u, v) < d(v) then
 9                d(v) := d(u) + w(u, v)
10                if v is not in Q then
11                    push v into Q
```

Q is « queue »
Works with FIFO queue
… but optimal with PriorityQueue (Dijkstra)

Libraries for Collection & Algorithms
big ecosystem, but jdk is often enough

Libraries of Interrest :

Guava (for Immutable Types)

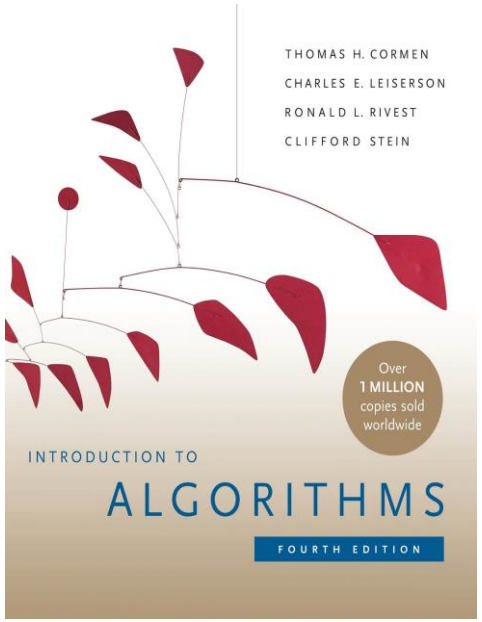
Specialized data structures for native types « ListInt » instead of « List<Integer> »

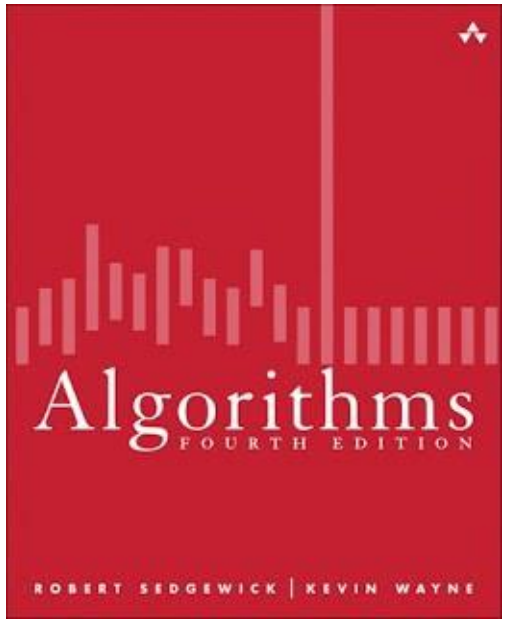
Specialized « Off-Heap Memory » collections … for huge in-memory collections,
but no GC problems with big jvm heap

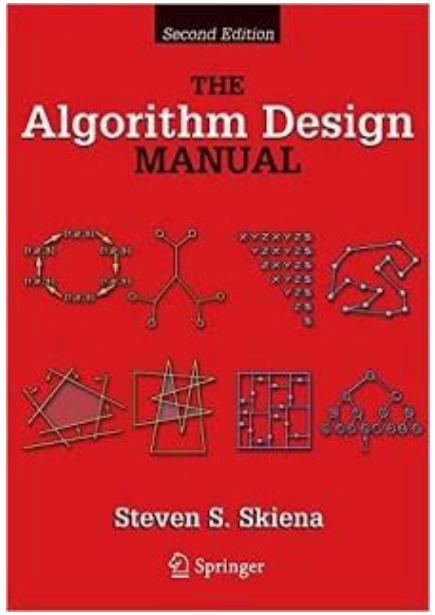
Disitributed collection … Spark Datasets

Specialized persistent collections (save to File ~Database)

More Links:
Books, Google, SourceCode, StackOverflow, …







Questions ?