Lecture 5 – Immutable Collections

SWS121: Secure Programming

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2024 Spring

Recall

- **Functions**
  - Methods vs Functions
  - Eta Expansion
  - Recursive Functions
  - Tail-Call Optimization
  - Default Parameter Values
  - Nested Methods
  - Multiple Parameter Lists
- **Pattern Matching**
  - Sealed Types
  - Regular Expression Patterns
  - Extractor Objects
- **Functional Error Handling**
  - Option Type
  - Try Type
  - Either Type

Contents

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Lists

Lists are **immutable** sequences of elements of the same type

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val list: List[Int]  = 3 :: 1 :: 2 :: 4 :: Nil
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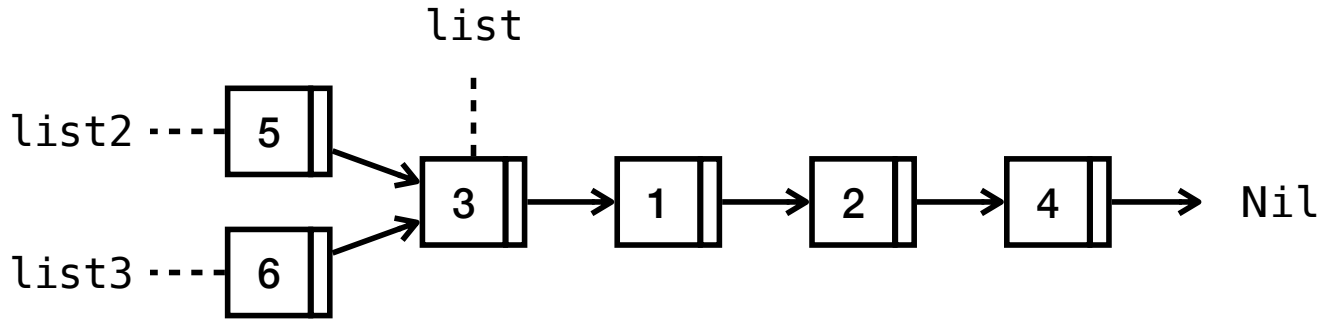

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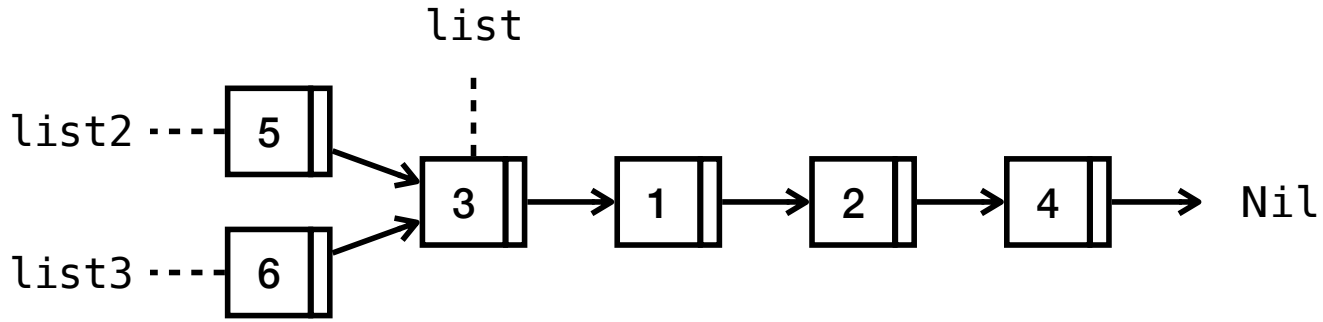

and support various **methods**:

```
list.size                          // 4                          : Int
list.map(_ * 2)                    // List(6, 2, 4, 8)           : List[Int]
list.filter(_ % 2 == 1)            // List(3, 1)                 : List[Int]
list.flatMap(x => List(x, -x))     // List(3, -3, ..., 4, -4)    : List[Int]
list.foldLeft(0)(_ + _)            // 0 + 3 + 1 + 2 + 4 = 10     : Int
```

Options, Maps, and Sets

We learned other basic immutable collections:

- `Option[T]`: represents **optional** values
- `Map[K, V]`: represents a collection of **key-value** pairs
- `Set[T]`: represents a collection of **unique** elements

```
val opt: Option[Int]      = Some(5)
val map: Map[String, Int] = Map("one" -> 1, "two" -> 2)
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PLRG

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```
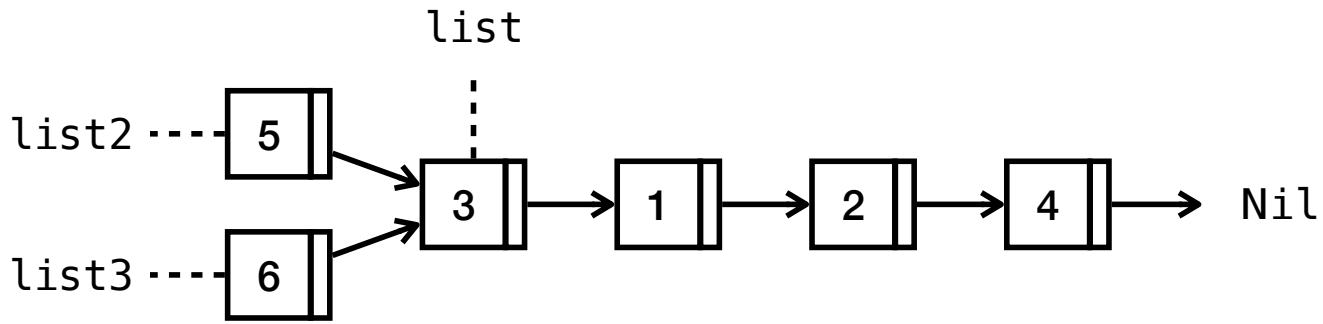

and support similar **methods**:

```
opt.size                        // 1                        : Int
set.map(_ * 2)                  // Set(2, 4, 6, 8)          : Set[Int]
map.filter((k, v) => v < 2)     // Map("one" -> 1)          : Map[String, Int]
opt.flatMap(x => Some(x * 2)) // Some(10)                   : Option[Int]
set.foldLeft(1)(_ * _)          // 1 * 1 * 2 * 3 * 4 = 24   : Int
```

Contents

Why Immutable Collections?



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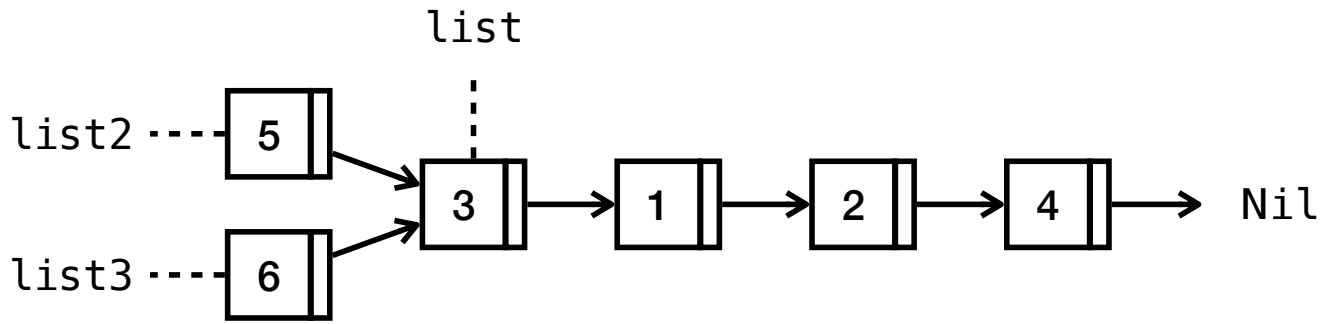

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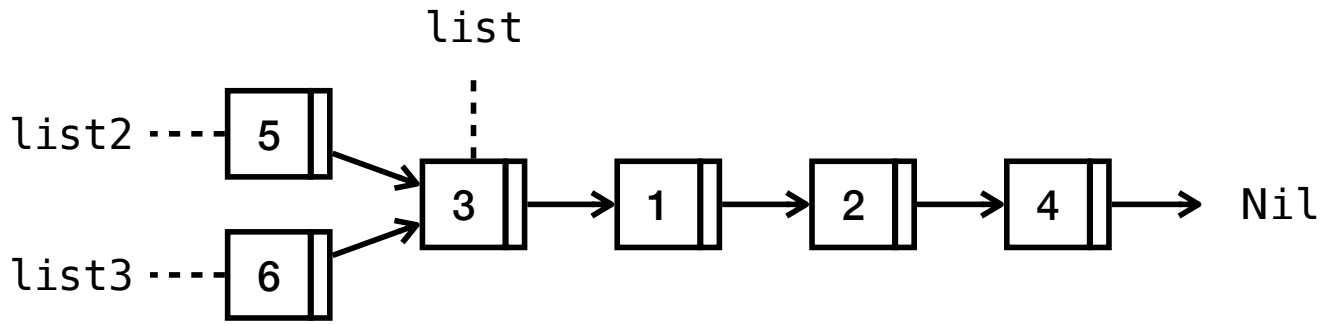

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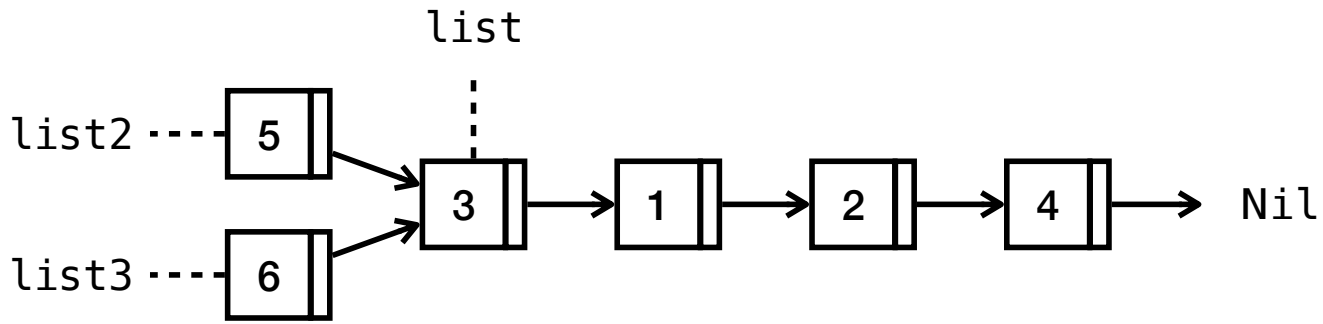

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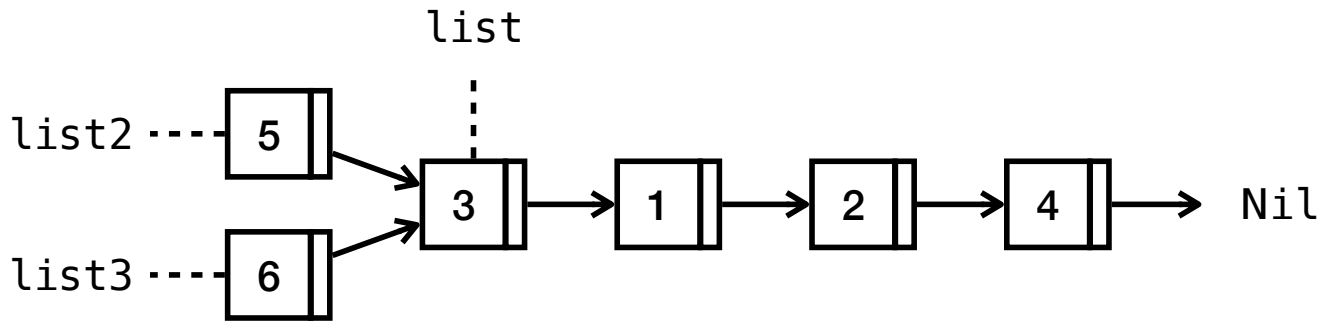

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- **Security:** We can avoid bugs caused by unintended modifications from external libraries or other parts of the code.
- **Easier Debugging**: There is no need to trace changes in the code that might have altered the value of an immutable object.
- **Memory Efficiency**: Immutable collections are more memory-efficient as they can share common parts of their structure instead.

Contents

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PLRG

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- Let's explore the collections hierarchy in Scala.

Trait Iterable

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It defines the following **concrete methods**:

Category	Methods
Addition	`concat (++)`
Map	`map, flatMap, collect`
Conversions	`to, toList, toVector, toMap, toSet, toSeq, toIndexedSeq, toBuffer, toArray`
Copying	`copyToArray`
Size Info	`isEmpty, nonEmpty, size, knownSize, sizeIs`
Element	`head, last, headOption, lastOption, find`
Sub-collection	`tail, init, slice, take, drop, takeWhile, dropWhile, filter, filterNot, withFilter`
Subdivision	`splitAt, span, partition, partitionMap, groupBy, groupMap, groupMapReduce`
Element Tests	`exists, forall, count`
Folds	`foldLeft, foldRight, reduceLeft, reduceRight`
Specific Folds	`sum, product, min, max`
String Operations	`mkString, addString`
View	`view`

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def hasNext: Boolean  // Check if there is a next element available
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def headOption: Option[A] =
  val it = iterator
  if (it.hasNext) Some(it.next()) else None
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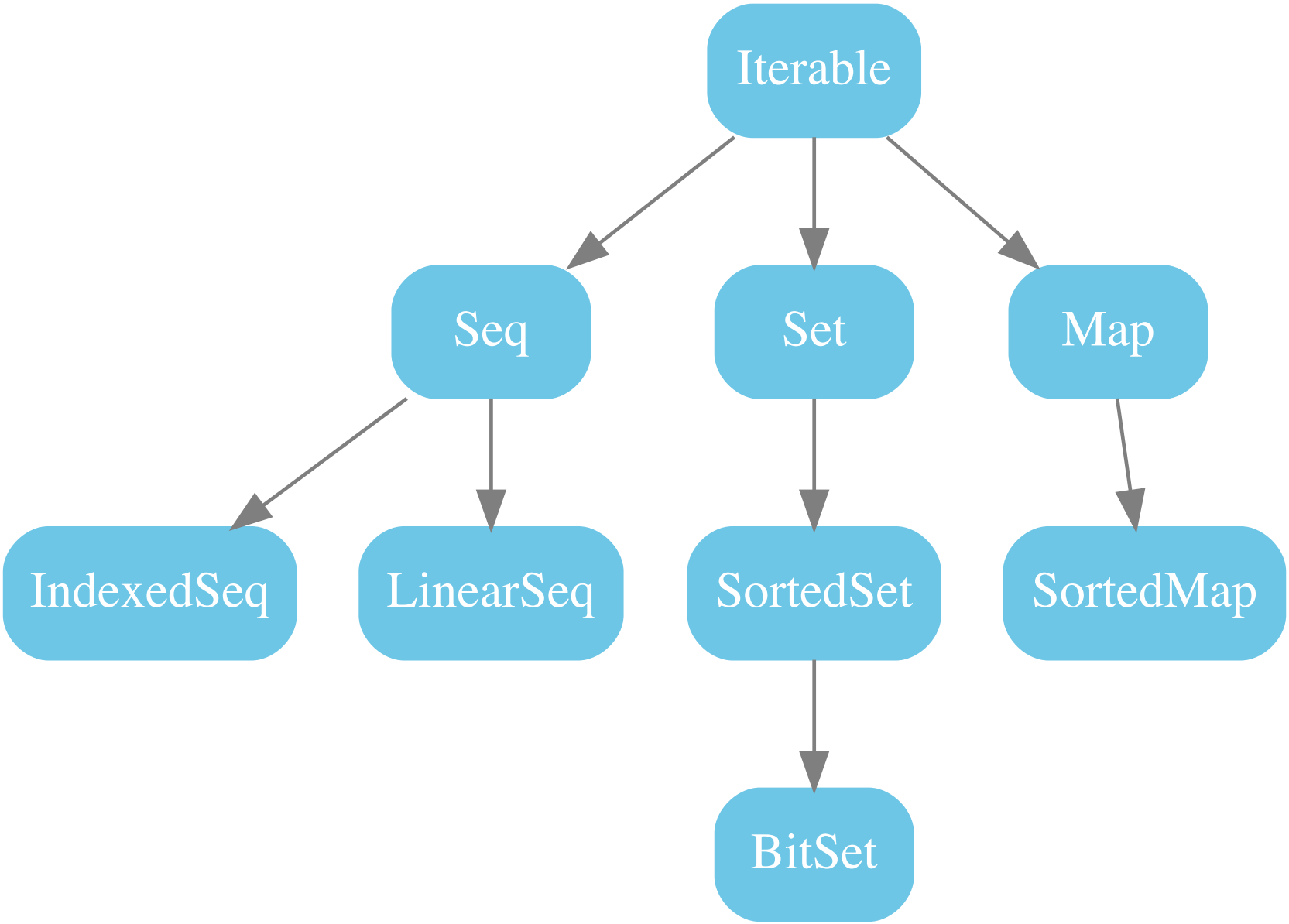
```

Then, we can use the `headOption` method as follows:

```
Nil.headOption            // None
List(1, 2, 3).headOption  // Some(1)
```

Collections Hierarchy



Immutable Collections Hierarchy

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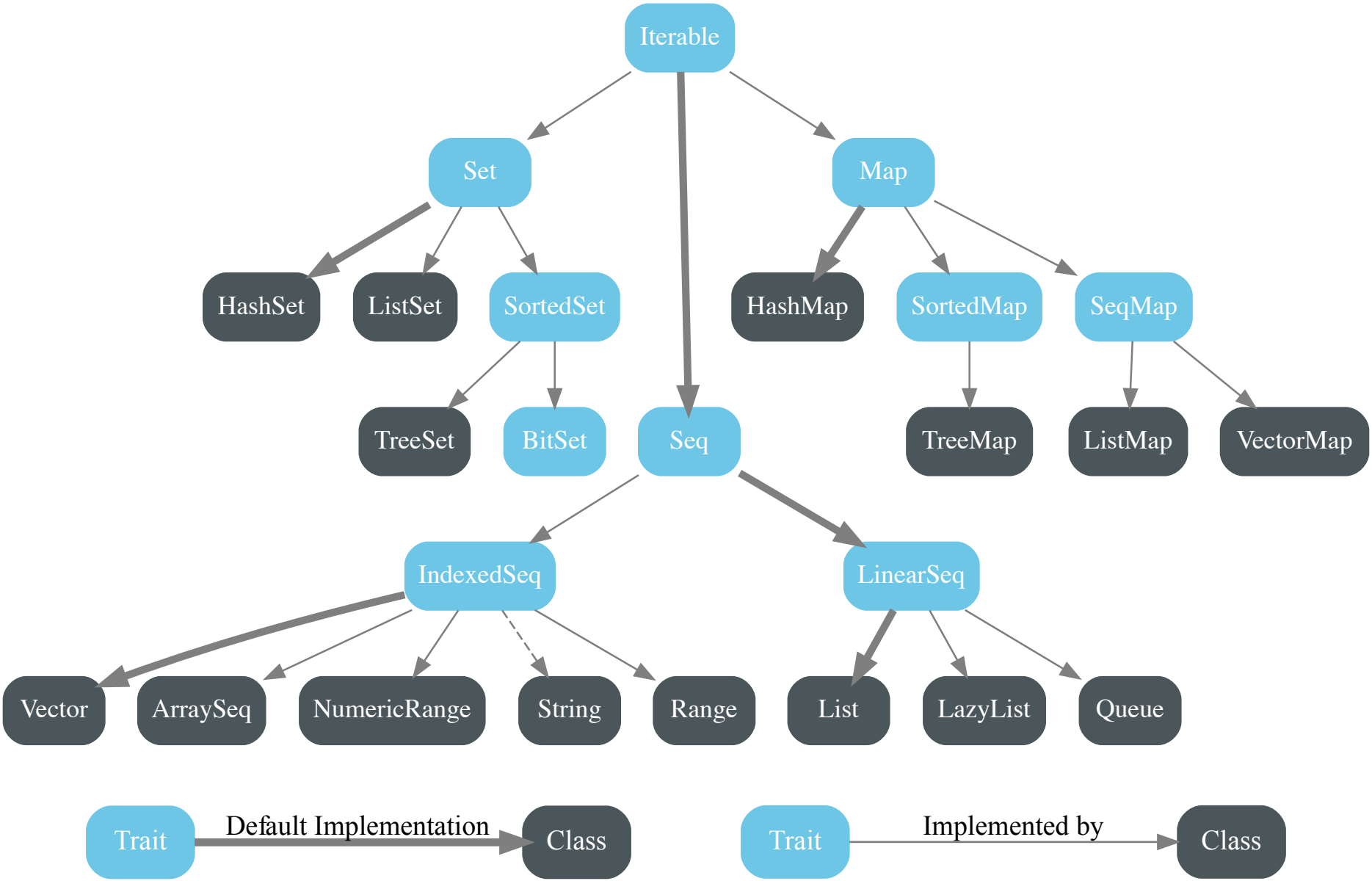

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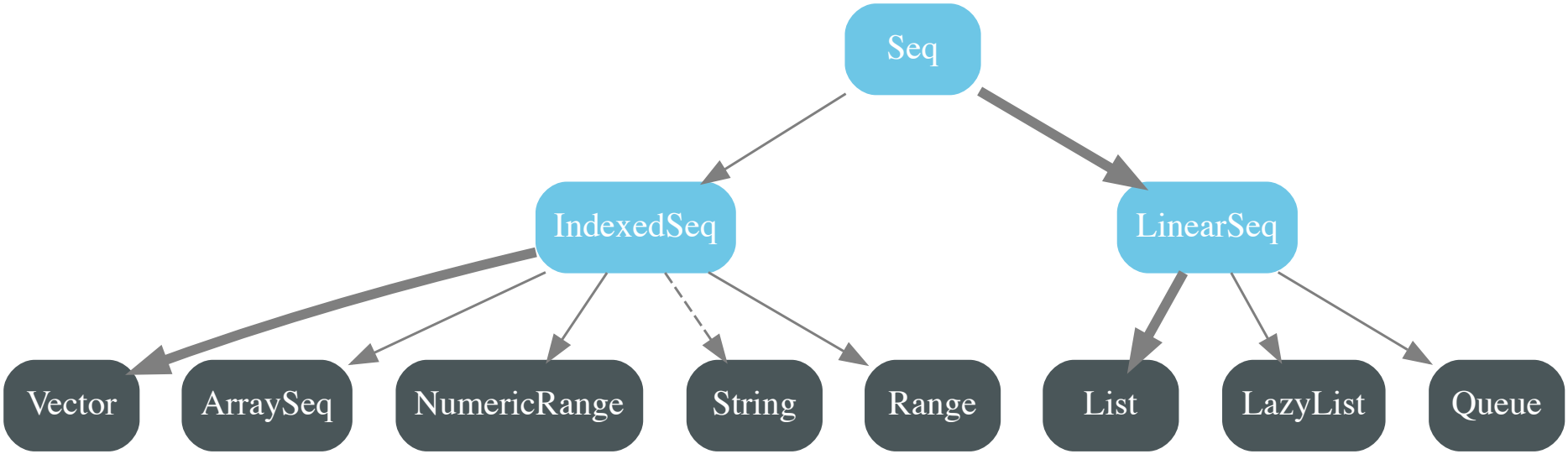
Sequences



- **IndexedSeq**: A sequence of elements with efficient **random access**.

```
val seq: IndexedSeq[Int] = ArraySeq(0, 1, 2, 3, 4)
seq(3)                   // 3                    (constant time)
```

- **LinearSeq**: A sequence of elements with efficient **linear access**.

```
val list: LinearSeq[Int] = List(0, 1, 2, 3, 4)
list.head                // 0                    (constant time)
list.tail                // List(1, 2, 3, 4)     (constant time)
```

Indexed Sequence – ArraySeq

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However, the time complexity of `prepend`, `update`, `prepend`, and `append` is **linear time** because we need to **copy all elements**.

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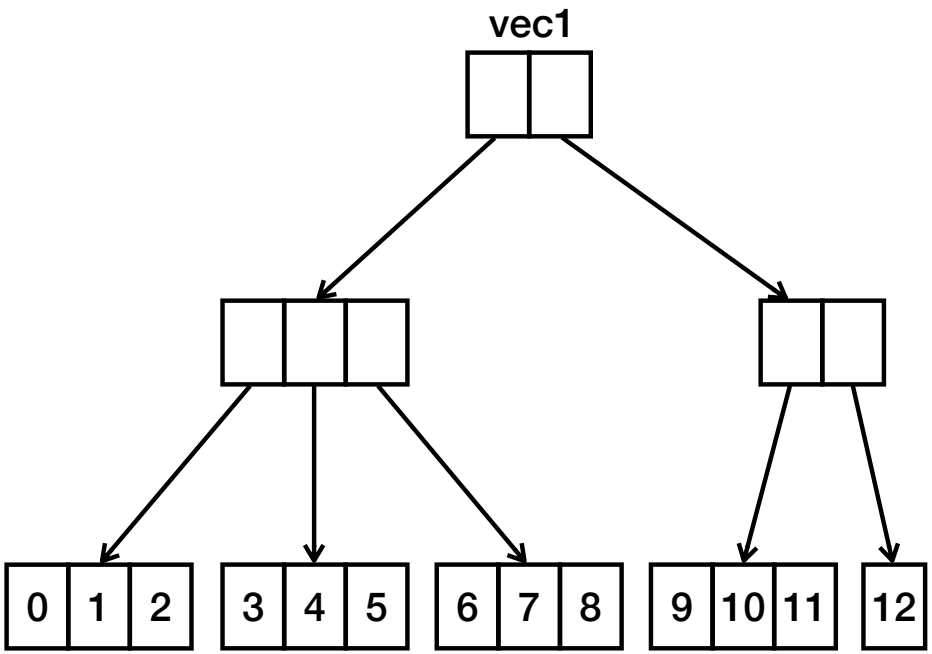
```
val vec1: Vector[Int] = Vector(0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12)
```



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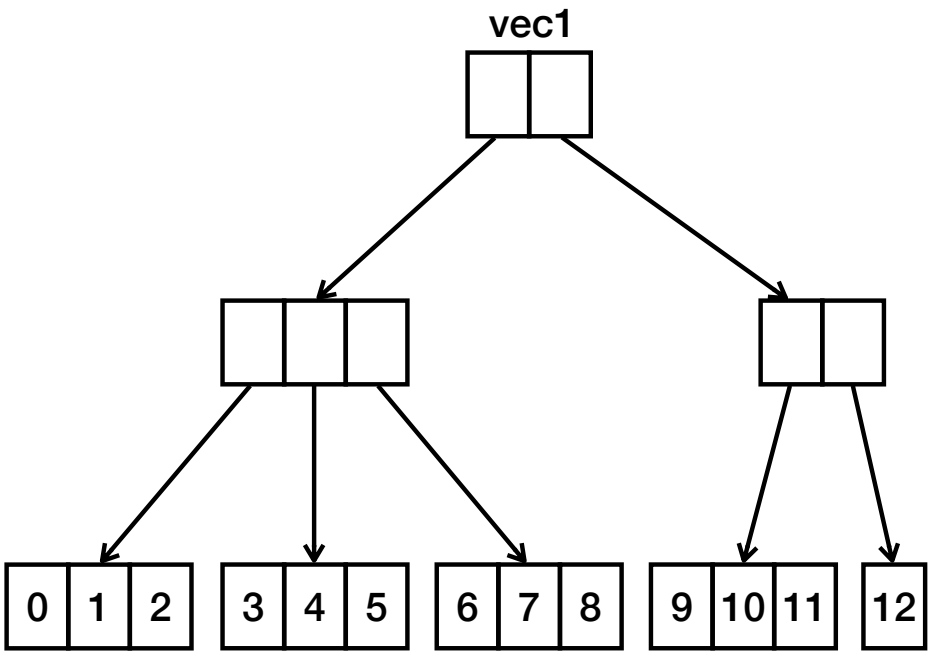
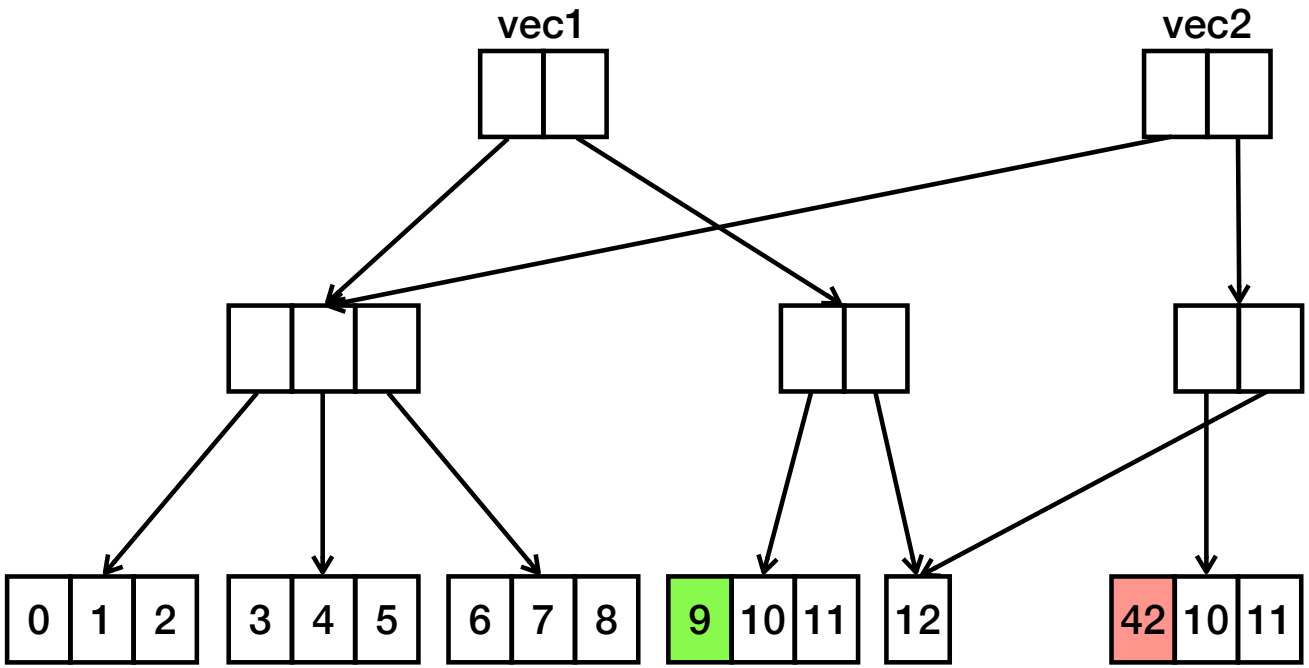


The indexing operation is **effectively constant time** because the depth of the tree is **logarithmic** in the number of elements.

```
vec1(9)  // 9
```

Indexed Sequence – Vector



The update operation is also **effectively constant time** because the depth of the tree is **logarithmic** in the number of elements.

It is memory-efficient because it **shares common parts** of the tree.

```
val vec2 = vec1.updated(9, 42)
```

Indexed Sequence – Vector

PLRG

- In fact, vectors are represented as variants of 32-wide trees.[1]

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- **Five hops** for vectors with up to $2^{30} \approx 1$ billion elements.
- So for all vectors of reasonable size, an element selection involves up to 5 primitive array selections.
- This is why the time complexity of element access is **effectively constant time**.

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For example, consider the following range:

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val range: Range = Range(2, 28, 3)
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It represents the range **starting** from 2 and **ending** at 28 with a **step** of 3:

$$2, 5, 8, 11, 14, 17, 20, 23, 26$$

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We can define ranges also using the methods (`to`, `until`, and `by`):

```
0 to 10          // Range(0, 1, 2, ..., 10)
0 to 10 by 2     // Range(0, 2, 4, 6, 8, 10)
0 until 10       // Range(0, 1, 2, ..., 9)
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```

The time complexity of `apply` is **constant time** because we can compute the element using the formula:

$$\texttt{start} + \texttt{step} \times \texttt{index}$$

Linear Sequence – Queue

We can treat a **List** as a **stack** by using the `::` operator for **pop** and `head/tail` methods for **push**.

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We can treat a **List** as a **stack** by using the `::` operator for **pop** and `head/tail` methods for **push**.

By combining **two lists**, we can implement a **queue**:

- The **enqueue** operation is implemented by **pushing** the elements to the `in` list.

- The **dequeue** operation is implemented by 1) **moving** the elements from the `in` list to the `out` list only when the `out` list is empty and 2) **poping** an element from the `out` list.

Linear Sequence – Queue

```
val q1 = Queue().enqueue(1).enqueue(2).enqueue(3)
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val q3 = q2.enqueue(4).enqueue(5).enqueue(6)
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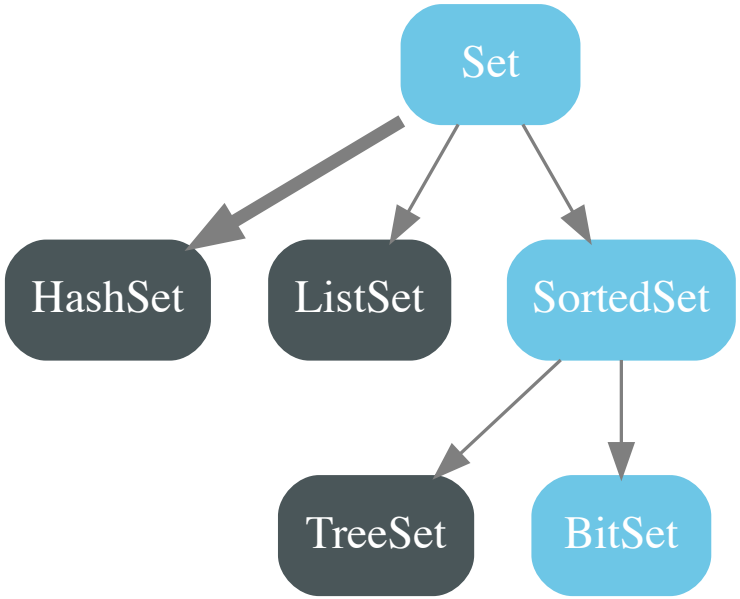
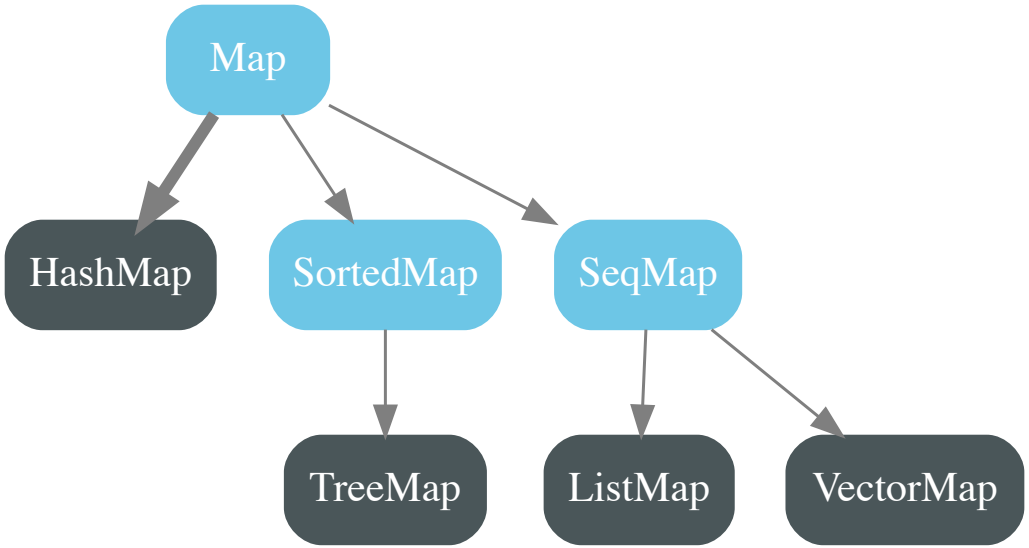
```
val (y, q4) = q3.dequeue      // y == 2
```

Contents

Sets and Maps





- **HashSet/HashMap**: A set/map of elements with **no order**.
- **TreeSet/TreeMap**: A set/map of elements with **sorted order**
- **BitSet**: A set of bits with **dense packing**.
- **VectorMap**: A map of elements with **insertion order**.

HashSet and HashMap

HashSet and **HashMap** are sets and maps of elements with **no order** using a **compressed hash-array mapped prefix-tree (CHAMP)**[2], which is a variant of the **hash-array mapped trie (HAMT)**.

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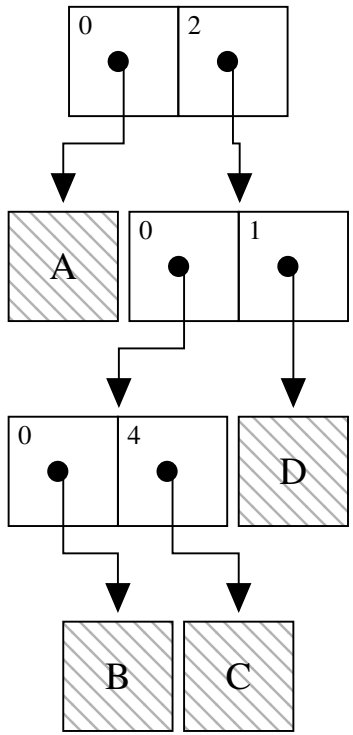
Following shows an example of a HAMT with 32-ary nodes:

$$hash(A) = 32_{10} = 0\ 1\ 0\ _{32}$$

$$hash(B) = 2_{10} = 2\ 0\ 0\ _{32}$$

$$hash(C) = 4098_{10} = 2\ 0\ 4\ _{32}$$

$$hash(C) = 34_{10} = 2\ 1\ 0\ _{32}$$



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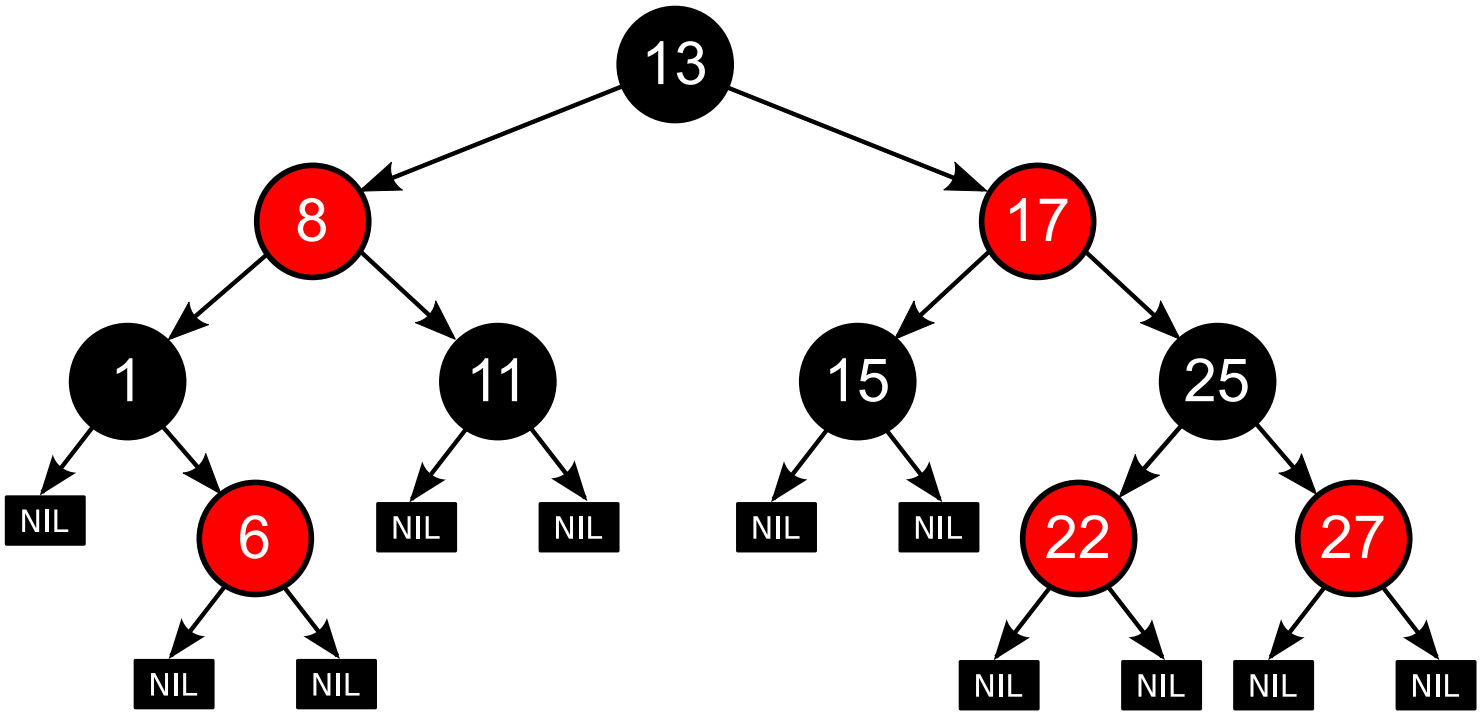
For example, the following set is represented as a red-black tree:

```
val set = Set(1, 6, 8, 11, 13, 15, 17, 25, 22, 27)
```



Contents

Performance Characteristics

	`head`	`tail`	`apply`	`update`	`prepend`	`append`
List	C	C	L	L	C	L
ArraySeq	C	L	C	L	L	L
Vector	eC	eC	eC	eC	eC	eC
Queue	aC	aC	L	L	L	C
Range	C	C	C	-	-	-
String	C	L	C	L	L	L

	`lookup`	`add`	`remove`	`min`
HashSet/HashMap	eC	eC	eC	L
TreeSet/TreeMap	Log	Log	Log	Log
BitSet	C	L	L	eC[3]
VectorMap	eC	eC	aC	L
ListMap	L	L	L	L

where **L** = linear time, **Log** = logarithmic time, **C** = constant time, **eC** = effectively constant time, and **aC** = amortized constant time.

[3] Assuming bits are densely packed.

Summary

PLRG

1. Recall: Basic Immutable Collections
   - Lists, Options, Maps, and Sets
2. Why Immutable Collections?
3. Collections Hierarchy
4. Sequences
   - ArraySeq
   - Vector
   - Range
   - Queue
5. Sets and Maps
   - HashSet and HashMap
   - TreeSet and TreeMap
6. Performance Characteristics

Next Lecture

- For Comprehensions

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