CS 351
Design of Large Programs
Complex Data Structures

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What is a Data Structure?

A data structure is defined by:

- an organization of the data being stored
- a set of operations for effective access to this data

Algorithmic complexity (efficiency) is directly tied to data organization

- searching for an element in an unsorted array takes linear time: $2^{32} = 4,294,967,296$
- searching for an element in a sorted array takes logarithmic time: 32

Key to computing efficiency is reducing algorithmic complexity

Relation to Abstract Data Types

Abstract Data Type specifications are given in terms of:

- an abstract data representation
- a set of operations over the abstract representation
- signature or interface
- semantics

A data structure is a concrete realization of the ADT

- it should preserve encapsulation
- it can be analyzed with respect to performance
  - at the formal level – time and space complexity
  - at the execution level – runtime and resource usage

Common Data Structures

- Some basic data structures are built into the language
  - arrays
- Some data structures are provided in standard libraries
  - linked lists
  - hash tables
  - search trees
- Other data structures need to be explicitly coded
  - trees
  - graphs
- Generic types facilitate generality and reuse
- Java collections expand the range of ready to use common data structures
  - designed, coded, and optimized

Illustration: Linked List

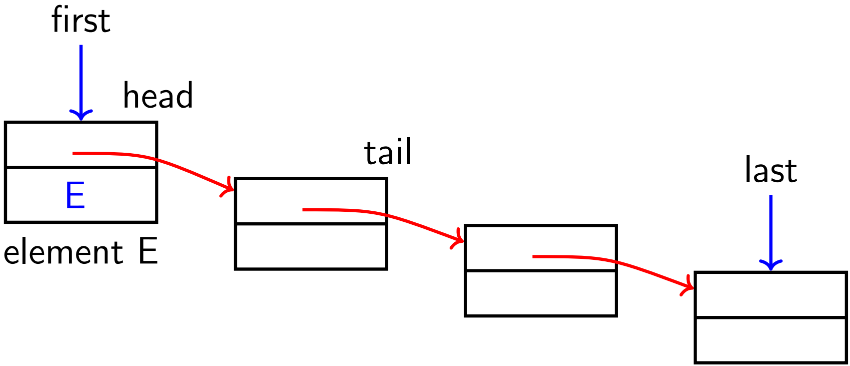


Illustration: Defining a Linked List in Java

```
public class LinkedList {
  private Node first;
  private Node last;

  public LinkedList() {
    last = first = null;
  }
  public void add(Object element) {
    // add element to the end
  }
  public void remove() {
    // remove element from the front
  }
  public Object getHead() {
    // return the head of the list
  }
  public LinkedList getTail() {
    // return the tail of the list
  }
}
```

Illustration: Defining a Node

```
public class Node {
  private Node next;
  private Object element;

  public Node(Object element, Node next) {
    this.element = element;
    this.next = next;
  }

  public Object getElement() { return element; }
  public void setElement() {
    this.element = element;
  }
  public Node getNext() { return next; }
  public void setNext(Node next) {
    this.next = next;
  }
}
```

Even better: Generics!

```
public class LinkedList<T> {
  private Node<T> first;
  private Node<T> last;

  //...
```

```
public class Node<T> {
  private Node<T> next;
  private T element;

  //...
```

Design Concerns: Memory Leaks

- Memory leaks are serious programming errors – hard to debug
- They happen when references are maintained to objects no longer in use
- The garbage collector cannot reclaim the space

Illustration: Memory Leaks

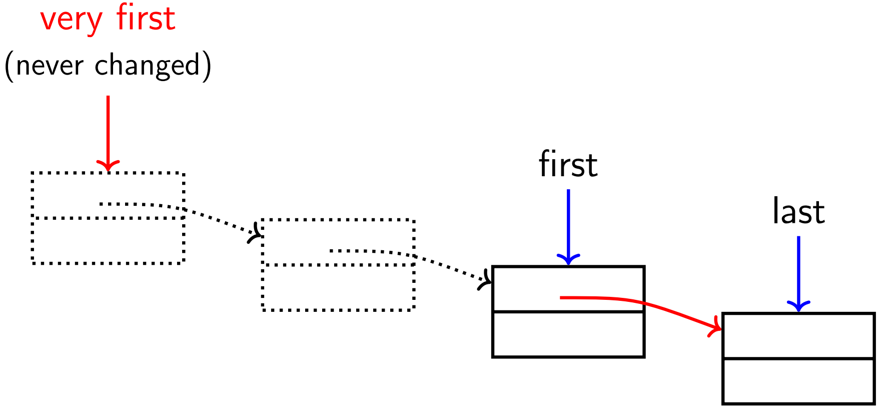
- Consider a new constructor creating a very first node

```
public LinkedList(Object element) {
  Node veryFirst = new Node(element, null);
  first = last = veryFirst;
}
```

- What if very first is a private field of LinkedList?

```
public LinkedList(Object element) {
  veryFirst = new Node(element, null);
  first = last = veryFirst;
}
```

Illustration: Memory Leaks



Design Concerns: Entanglement

- Assignment statements such as x = y result in both x and y referring to the same object
- changes carried out by invoking a method x.set(v)
  - alter the object
  - are visible to y when invoking y.get()
- Often this is not the desired outcome

Object Cloning

Cloning is a powerful, but controversial, feature in Java

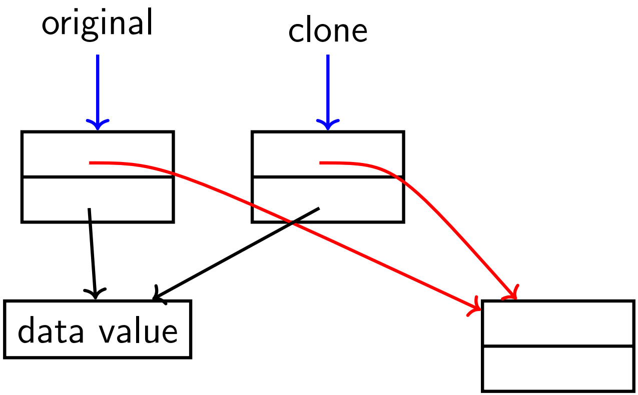
- Java provides two forms of cloning
  - *shallow* – a new object is created and the fields of the original are copied without change
    Default strategy provided by `Object.clone()`
  - *deep* – a new object is created and cloning is applied recursively to each field
    Must override `clone()` to implement this strategy
- Great care needs to be exercised to apply it correctly
- It is generally recommended to provide a *copy constructor*

Illustration: Incorrect Cloning

```
@Override
public Node clone() {
  try {
    return (Node) super.clone();
  }
  catch (CloneNotSupportedException e) {
    throw new InternalError(e.toString());
  }
}
```

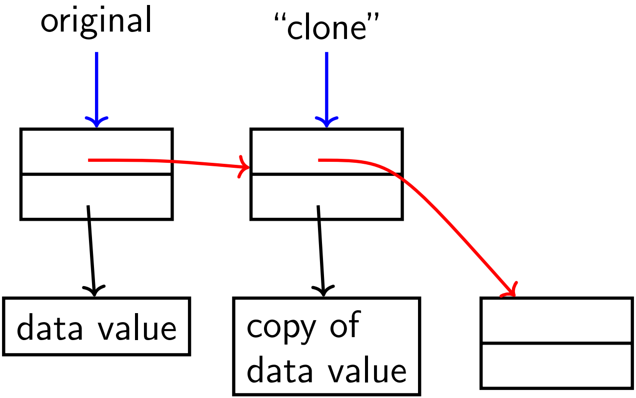
Using default clone implementation will just copy all fields. (This can be okay if all fields are primitives and/or immutable objects.)

Illustration: Incorrect Clone Result



Fields are just blindly duplicated.

Illustration: Desired Copy Action



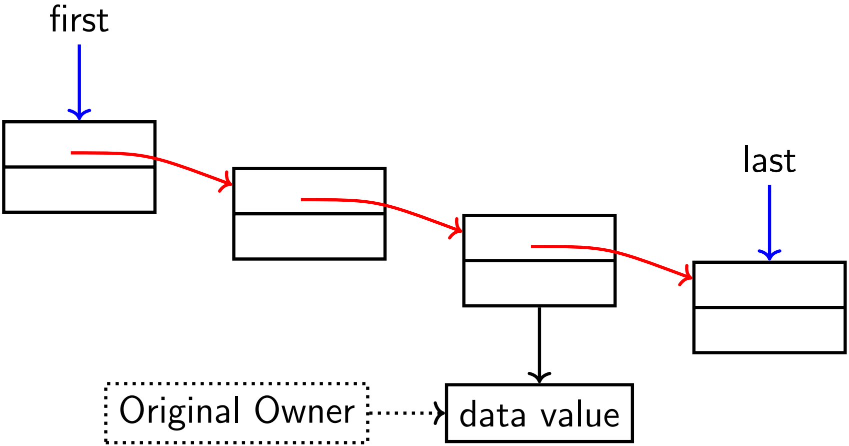
This is not cloning, rather tailored object duplication.

Design Concerns: Encapsulation Cracks

The object creator retaining access:

- exposes access to the data structure internals
- introduces side effects that break the class contract
- cloning/copying is one way to avoid this design flaw

Illustration: Creator Retaining Access



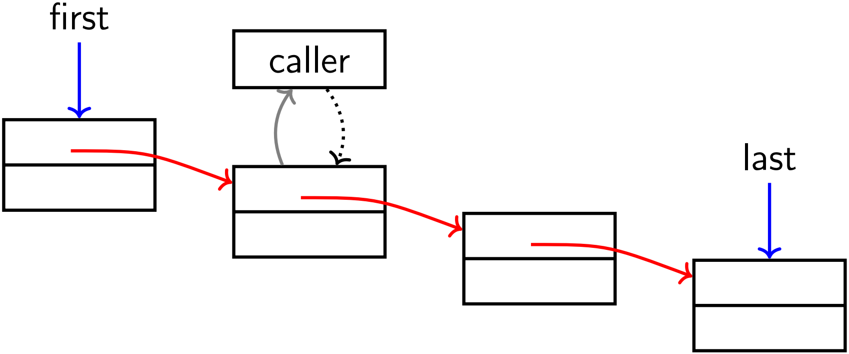
Original owner of data may still have access to it.

Design Concerns: Encapsulation Cracks

An internal object is returned to the caller

- providing access to the data structure internals
- enabling side effects that break the class contract
- creating the potential to break the integrity of the data structure

Illustration: Returning Internal Object



Returned node becomes accessible to caller.

Collections

Collections or *containers*:

- allow programmers to hold and organize sets of objects
- . . . in useful and efficient ways
- . . . as part of consistent and flexible framework
- Java provides us with many standard collection interfaces and implementations

Core Collection Interfaces

- Collection – root of the collection hierarchy
- Set – no duplicates
- List – ordered collection, sequence
- Queue – holds elements for processing
- Deque – double ended queue
- Map – maps keys to values

Collection Interface

- size, isEmpty
- contains
- add, addAll
- remove, removeAll, retainAll, clear
- toArray
- iterator (because Collection implements Iterable)

Optional methods that are not supported by a specific implementation throw `UnsupportedOperationException` (read the documentation!)

List

- add, addAll – add to end of the list
- remove – removes first occurrance
- iterator, listIterator
- indexOf, lastIndexOf – find index of elememt
- get, set – access element at given index
- subList – view portion of list as a List

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What data structure could you use to implement a List?

Queue

- Insert – add, offer
- Remove – remove, poll
- Examine – element, peek

Queues usually use FIFO order. `PriorityQueue` will use natural ordering or a Comparator.

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What data structure could you use to implement a Queue?

Map

Maps keys to values. Does not implement `Collection` itself, but has three *collection views*

- `keySet` – Set of the keys
- `values` – Collection of values
- `entrySet` – Set of key-value mappings.

Beware of using mutable objects as keys!

- put – associate a key with a value
- get – get value associated with key
- remove – remove key/value mapping
- containsKey, containsValue

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Iterator and Iterable

Iterator has three methods

- hasNext – Are there more elements?
- next – Return the next element
- remove – Remove the last element returned (optional)

Iterable only has one method

- iterator – returns an Iterator
- Implementing this interface allows object to be target of for-each

Iterator

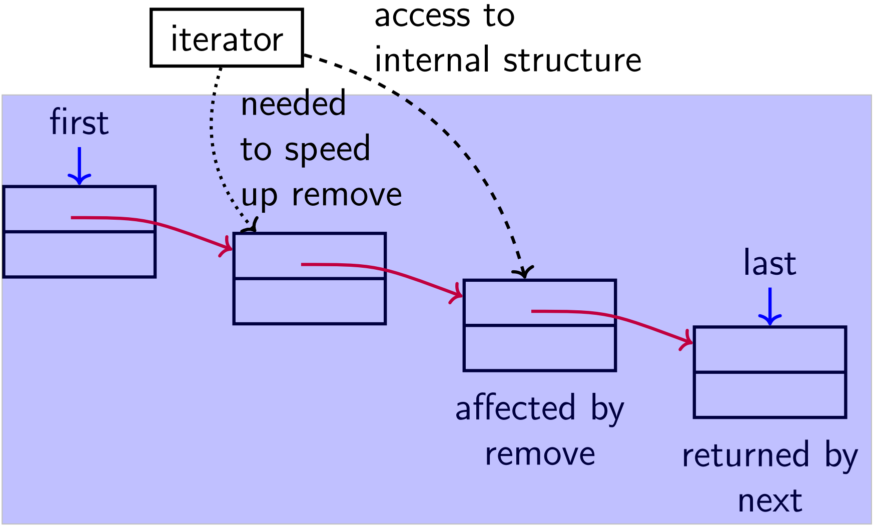
- The ability to examine an entire collection of objects is a helpful feature
- Java provides the Iterable interface specifically for this purpose
- A specific iterator may or may not take a snapshot first
- If not, use of other methods may affect the results

Iterator: Protecting Encapsulation

The iterator:

- is made available outside the collection
- does not reveal anything about the internal organization
- has access to the internal organization of the data

Iterator: Protecting Encapsulation



Data Structure Design

Research has led to the development of an arsenal of specialized data structures

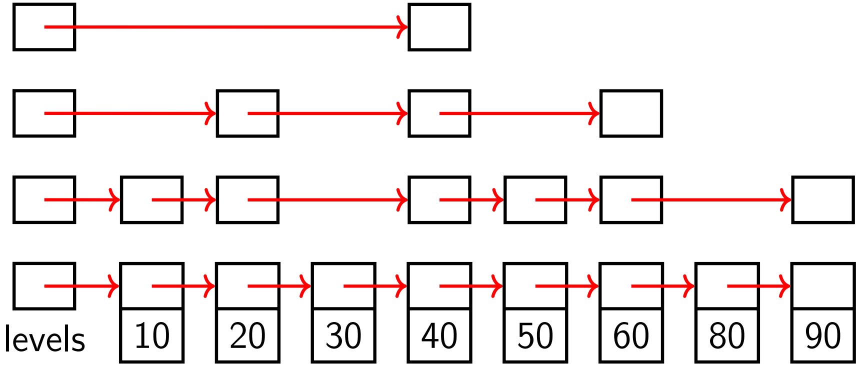
- Search and use them when developing a new program
- Don't reinvent the wheel

Example: Skip List

One such data structure is a Skip List:

- optimized for fast search in ordered lists
- multiple linked lists form express lanes supporting list traversal
- stops along each lane are determined using some probability p

Illustration: Skip List



Example: Game of Life

The Game of Life is a cellular automaton devised by the British mathematician John Horton Conway in 1970.

- Given a finite, two-dimensional, orthogonal grid of square cells.
- Each cell is in one of two possible states, Live or Dead.
- The initial pattern constitutes the 'seed' of the system.

Example: Game of Life

- Every cell interacts with its eight neighbors.
- At each step in time:
    - any live cell with fewer than two live neighbors dies, as if by loneliness
    - any live cell with more than three live neighbors dies, as if by overcrowding
    - any dead cell with exactly three live neighbors comes to life
- A new generation is created by applying the rules simultaneously to every cell.

Implementing Game of Life

How do we represent the game?

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How do we represent the game?

- Simple implementation: Two dimensional boolean array N by N
- What if N is very large?
- What if game is very sparse?