CSE373: Data Structures & Algorithms

Lecture 19: Software Design Interlude – Preserving Abstractions

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Announcements

- Midterm review tomorrow
- Midterm on Wednesday
- Partner selection for HW5 due Thursday
- Java Collections review on Thursday

Midterm Review

- Amortized complexity
  - the logic behind it
  - the definition and how to use it
  - the difference vs single operation worst case
- Union-find
  - the basic operations (find and union)
  - up trees and the array representation
  - asymptotic performance
  - the optimizations discussed in lecture
    - union-by-size
    - path compression

Midterm Review

- Hash tables
  - basic operations (find, insert, and delete)
  - client vs library responsibilities
  - hash functions
  - perfect hashing
- Hash collisions
  - resolution methods (process, relative merits)
    - separate chaining
    - probing (linear, quadratic, double hashing)
  - requirements for success (table size, load factor, etc.)
  - rehashing

Midterm Review

- Graphs
  - terminology (directed, undirected, weighted, connected, etc.)
    - paths, cycles
    - trees, DAGs
    - dense, sparse
  - notation
  - data structures (matrix, list)
    - structure, performance (time and space), relative merits
  - algorithms
    - topological sort
    - paths: BFS (also breadth-first traversal), DFS, Dijkstra's,
    - minimum spanning trees: Prim's, Kruskal's

Motivation

- Essential: knowing available data structures and their trade-offs
  - You're taking a whole course on it! ☺
- However, you will rarely if ever re-implement these "in real life"
  - Provided by libraries
- But the key idea of an *abstraction* arises *all the time* "in real life"
  - Clients do not know how it is implemented
  - Clients do not need to know
  - Clients cannot "break the abstraction" *no matter what they do*

Interface vs. implementation

- Provide a reusable interface without revealing implementation
- More difficult than it sounds due to aliasing and field-assignment
  - Some common pitfalls
- So study it in terms of ADTs vs. data structures
  - Will use priority queues as example in lecture, but any ADT would do
  - Key aspect of grading your homework on graphs

Recall the abstraction

Clients:

"not trusted by ADT implementer"

- Can perform any sequence of ADT operations
- Can do anything type-checker allows on any accessible objects

`new PQ(…)`

`insert(…)`

`deleteMin(…)`

`isEmpty()`

Data structure:

- Should document how operations can be used and what is checked (raising appropriate exceptions)
  - E.g., fields not **`null`**
- If used correctly, correct priority queue for any client
- Client "cannot see" the implementation
  - E.g., binary min heap

Our example

- A priority queue with to-do items, so earlier dates "come first"
  - Simpler example than using Java generics
- Exact method names and behavior not essential to example

```
public class Date {
    … // some private fields (year, month, day)
    public int getYear() {…}
    public void setYear(int y) {…}
    … // more methods
}
public class ToDoItem {
    … // some private fields (date, description)
    public void setDate(Date d) {…}
    public void setDescription(String d) {…}
    … // more methods
}
// continued next slide…
```

Our example

- A priority queue with to-do items, so earlier dates "come first"
  - Simpler example than using Java generics
- Exact method names and behavior not essential to example

```
public class Date { … }
public class ToDoItem { … }
public class ToDoPQ {
   … // some private fields (array, size, …)
   public ToDoPQ() {…}
   void insert(ToDoItem t) {…}
   ToDoItem deleteMin() {…}
   boolean isEmpty() {…}
}
```

An obvious mistake

- Why we trained you to "mindlessly" make fields **`private`**:

```
public class ToDoPQ {
    … // other fields
    public ToDoItem[] heap;
    public ToDoPQ() {…}
    void insert(ToDoItem t) {…}
    …
}
// client:
pq = new ToDoPQ();
pq.heap = null;
pq.insert(…); // likely exception
```

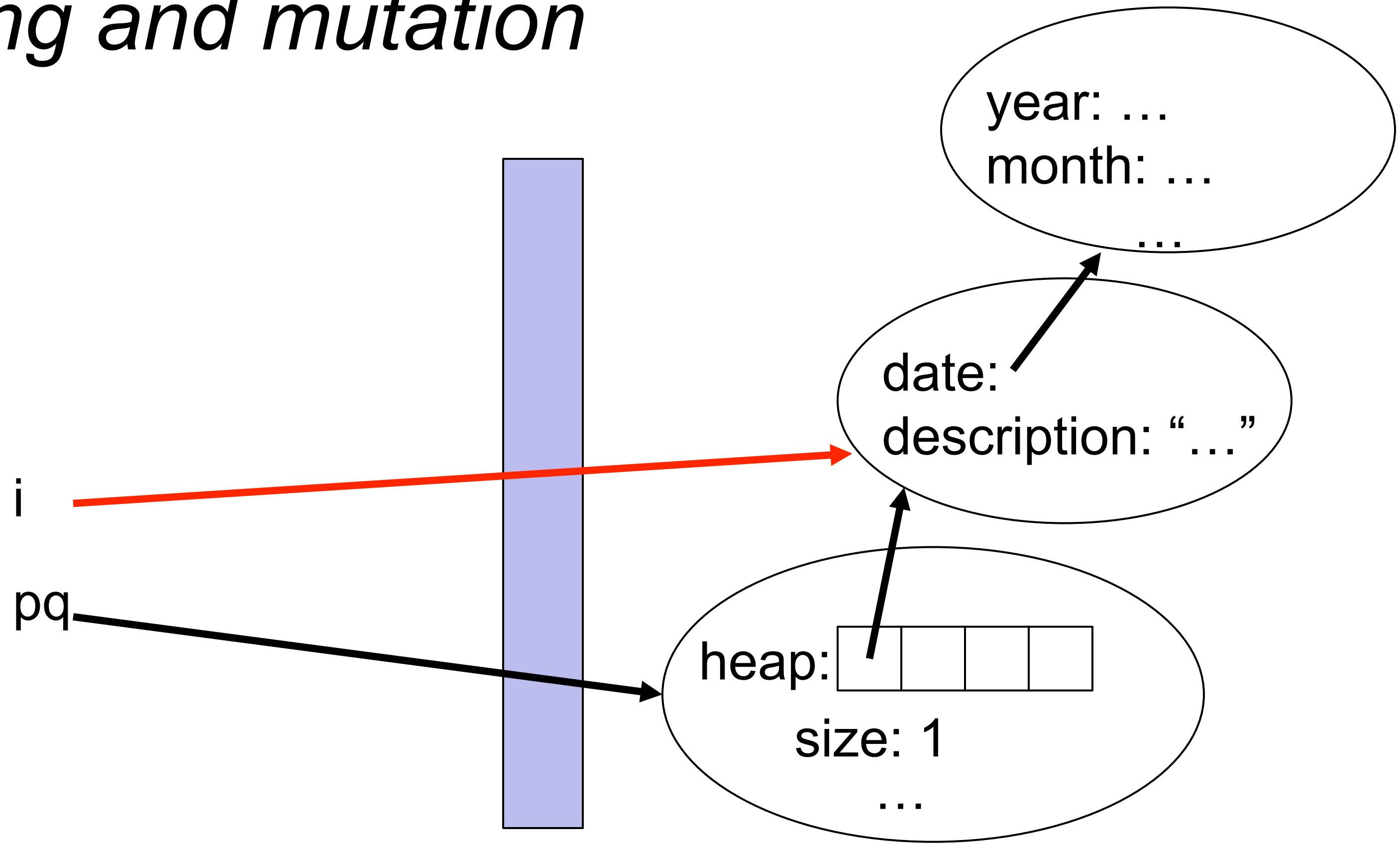
- Today's lecture: **`private`** does not solve all your problems!
  - Upcoming pitfalls can occur even with all **`private`** fields

Less obvious mistakes

```
public class ToDoPQ {
   … // all private fields
   public ToDoPQ() {…}
   void insert(ToDoItem i) {…}
   …
}

// client:
ToDoPQ   pq = new ToDoPQ();
ToDoItem i  = new ToDoItem(…);
pq.insert(i);
i.setDescription("some different thing");
pq.insert(i); // same object after update
x = deleteMin(); // x's description???
y = deleteMin(); // y's description???
```

Aliasing and mutation

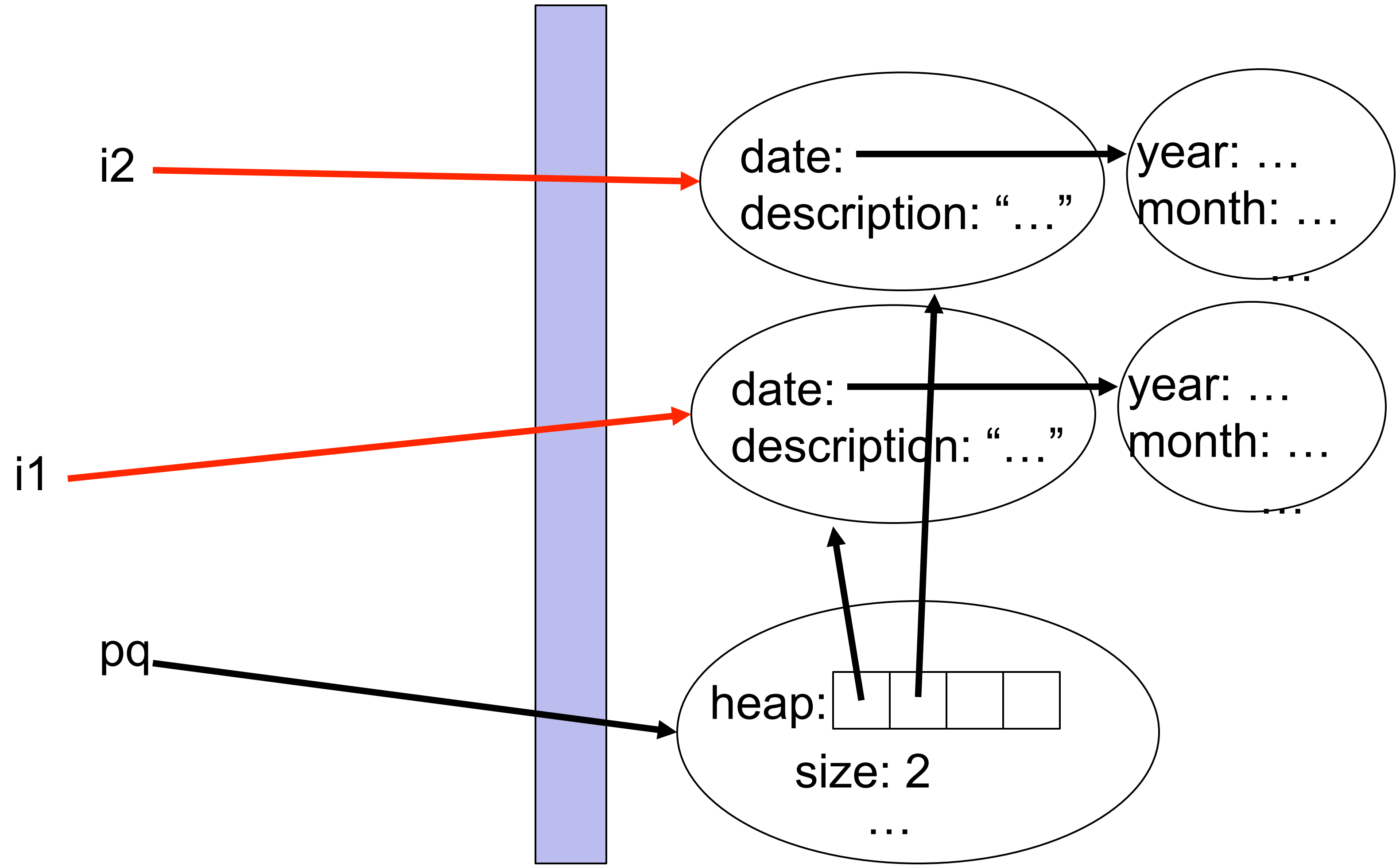


- Client was able to update something inside the abstraction because client had an alias to it!
  – It is too hard to reason about and document what should happen, so better software designs avoid the issue!

More bad clients

```
ToDoPQ   pq = new ToDoPQ();
ToDoItem i1 = new ToDoItem(…); // year 2013
ToDoItem i2 = new ToDoItem(…); // year 2014
pq.insert(i1);
pq.insert(i2);
i1.setDate(…); // year 2015
x = deleteMin(); // "wrong" (???) item?
       // What date does returned item have???
```

More bad clients



More bad clients

```
pq = new ToDoPQ();
ToDoItem i1 = new ToDoItem(…);
pq.insert(i1);
i1.setDate(null);
ToDoItem i2 = new ToDoItem(…);
pq.insert(i2); // NullPointerException???
```

Get exception inside data-structure code even if **`insert`** did a careful check that the date in the **`ToDoItem`** is not **`null`**

- Bad client later invalidates the check

The general fix

- Avoid aliases into the internal data (the “red arrows”) by copying objects as needed
  - Do not use the same objects inside and outside the abstraction because two sides do not know all mutation (field-setting) that might occur
  - “Copy-in-copy-out”
- A first attempt:

```
public class ToDoPQ {
   …
   void insert(ToDoItem i) {
     ToDoItem internal_i =
       new ToDoItem(i.date,i.description);
     … // use only the internal object
   }
}
```

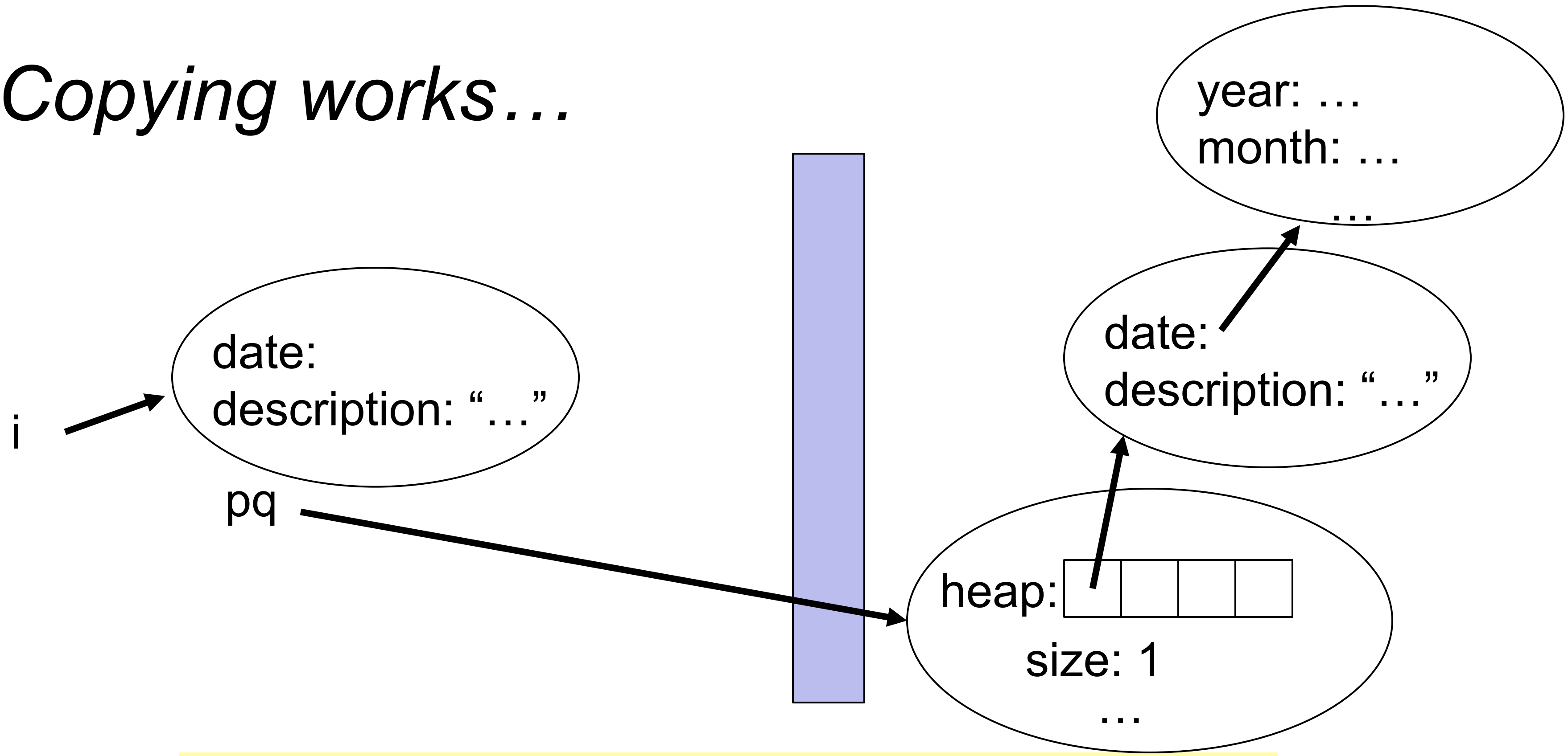
Must copy the object

```
public class ToDoPQ {
   …
   void insert(ToDoItem i) {
     ToDoItem internal_i =
       new ToDoItem(i.date,i.description);
     … // use only the internal object
   }
}
```

- Notice this version accomplishes nothing
  - Still the alias to the object we got from the client:

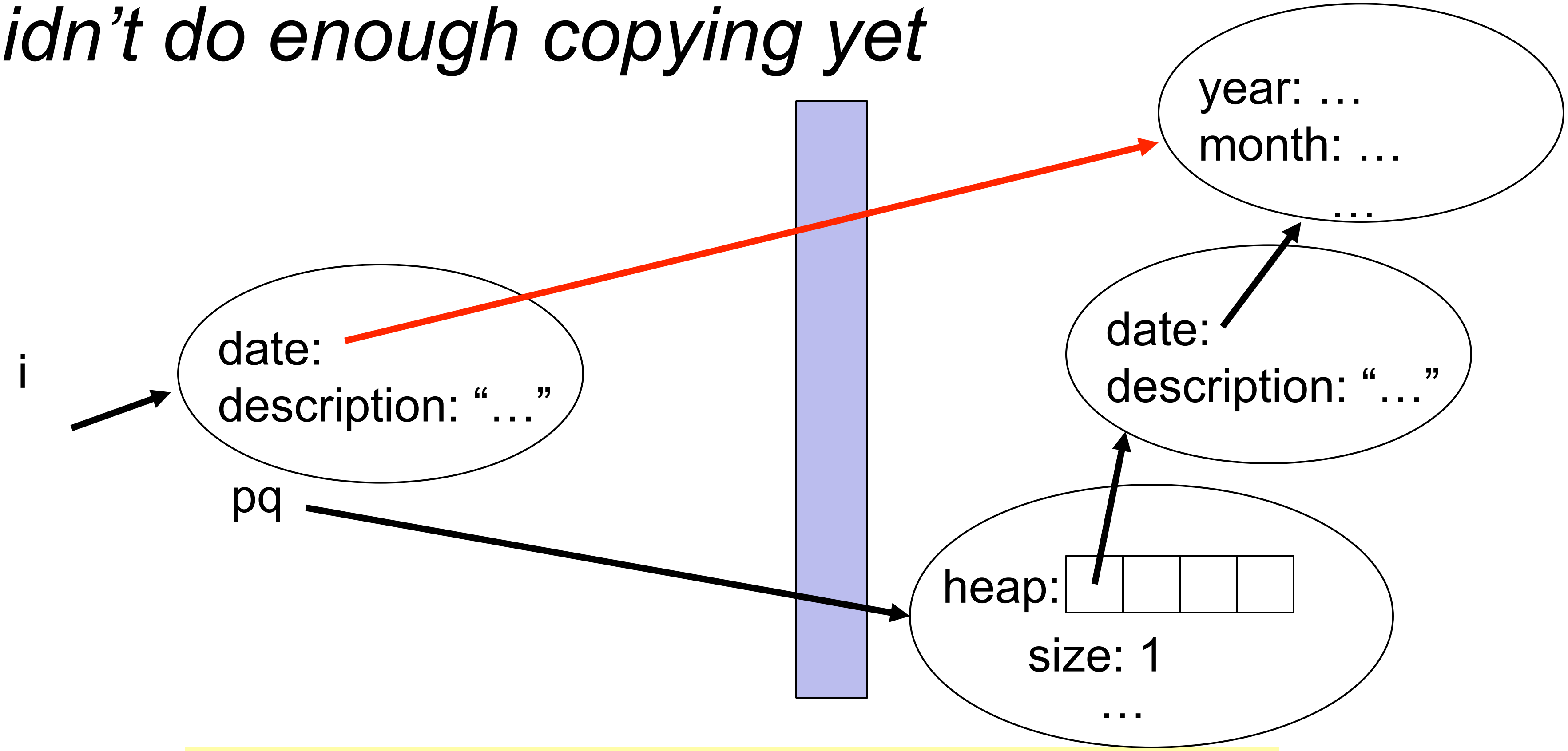
```
public class ToDoPQ {
   …
   void insert(ToDoItem i) {
     ToDoItem internal_i = i;
     … // internal_i refers to same object
   }
}
```

Copying works…




```
ToDoItem i = new ToDoItem(…);
pq = new ToDoPQ();
pq.insert(i);
i.setDescription("some different thing");
pq.insert(i);
x = deleteMin();
y = deleteMin();
```

Didn't do enough copying yet




```
Date d = new Date(…)
ToDoItem i = new ToDoItem(d,"buy beer");
pq = new ToDoPQ();
pq.insert(i);
d.setYear(2015);
…
```

Deep copying

- For copying to work fully, usually need to also make copies of all objects referred to (and that they refer to and so on…)
  - All the way down to **`int`**, **`double`**, **`String`**, …
  - Called *deep copying* (versus our first attempt *shallow-copy*)

- Rule of thumb: Deep copy of things passed into abstraction

```
public class ToDoPQ {
   …
   void insert(ToDoItem i) {
     ToDoItem internal_i =
       new ToDoItem(new Date(…),
                    i.description);
     … // use only the internal object
   }
}
```

Constructors take input too

- General rule: Do not “trust” data passed to constructors
  - Check properties and make deep copies
- Example: Floyd’s algorithm for **`buildHeap`** should:
  - Check the array (e.g., for **`null`** values in fields of objects or array positions)
  - Make a deep copy: new array, new objects

```
public class ToDoPQ {
  // a second constructor that uses
  // Floyd's algorithm, but good design
  // deep-copies the array (and its contents)
  void PriorityQueue(ToDoItem[] items) {
     …
  }
}
```

That was copy-in, now copy-out…

- So we have seen:
  – Need to deep-copy data passed into abstractions to avoid pain and suffering

- Next:
  – Need to deep-copy data passed out of abstractions to avoid pain and suffering (unless data is “new” or no longer used in abstraction)

- Then:
  – If objects are immutable (no way to update fields or things they refer to), then copying unnecessary

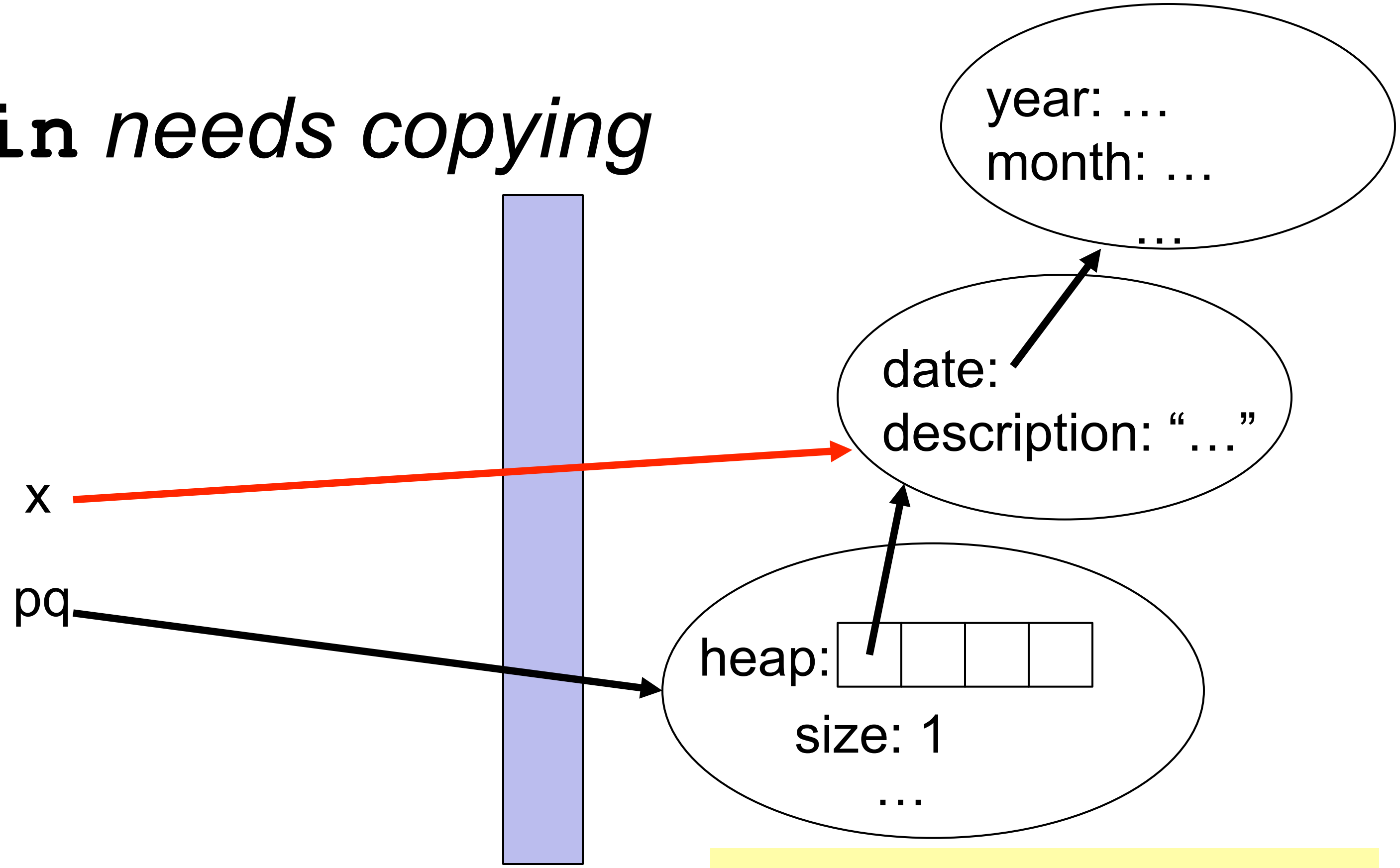
`deleteMin` *is fine*

```
public class ToDoPQ {
    …
    ToDoItem deleteMin() {
      ToDoItem ans = heap[0];
      … // algorithm involving percolateDown
      return ans;
}
```

- Does not create a “red arrow” because object returned is no longer part of the data structure

- Returns an alias to object that was in the heap, but now it is not, so conceptual “ownership” “transfers” to the client

`getMin` *needs copying*




```
ToDoItem i = new ToDoItem(…);
pq = new ToDoPQ();
x = pq.getMin();
x.setDate(…);
```

```
public class ToDoPQ {
  ToDoItem getMin() {
    int ans = heap[0];
    return ans;
  }
}
```

- Uh-oh, creates a "red arrow"

The fix

- Just like we deep-copy objects from clients before adding to our data structure, we should deep-copy parts of our data structure and return the copies to clients

- Copy-in *and* copy-out

```
public class ToDoPQ {
  ToDoItem getMin() {
    int ans = heap[0];
    return new ToDoItem(new Date(…),
                        ans.description);
  }
}
```

Less copying

- (Deep) copying is one solution to our aliasing problems

- Another solution is *immutability*
  - Make it so nobody can ever change an object or any other objects it can refer to (deeply)
  - Allows "red arrows", but immutability makes them harmless

- In Java, a **`final`** field cannot be updated after an object is constructed, so helps ensure immutability
  - But **`final`** is a "shallow" idea and we need "deep" immutability

This works

```
public class Date {
   private final int year;
   private final String month;
   private final String day;
}
public class ToDoItem {
   private final Date date;
   private final String description;
}
public class ToDoPQ {
   void insert(ToDoItem i){/*no copy-in needed!*/}
   ToDoItem getMin(){/*no copy-out needed!*/}
   …
}
```

Notes:

- **`String`** objects are immutable in Java
- (Using **`String`** for **`month`** and **`day`** is not great style though)

This does not work

```
public class Date {
   private final int year;
   private String month; // not final
   private final String day;
   …
}
public class ToDoItem {
   private final Date date;
   private final String description;
}
public class ToDoPQ {
   void insert(ToDoItem i){/*no copy-in*/}
   ToDoItem getMin(){/*no copy-out*/}
   …
}
```

Client could mutate a **`Date`**'s **`month`** that is in our data structure

- So must do entire deep copy of **`ToDoItem`**

`final` *is shallow*

```
public class ToDoItem {
   private final Date date;
   private final String description;
}
```

- Here, **`final`** means no code can update the **`date`** or **`description`** fields after the object is constructed
- So they will always refer to the same **`Date`** and **`String`** objects
- But what if those objects have *their* contents change
  - Cannot happen with **`String`** objects
  - For **`Date`** objects, depends how we define **`Date`**
- So **`final`** is a “shallow” notion, but we can use it “all the way down” to get deep immutability

This works

- When deep-copying, can “stop” when you get to immutable data
  - Copying immutable data is wasted work, so poor style

```
public class Date { // immutable
   private final int year;
   private final String month;
   private final String day;
   …
}
public class ToDoItem {
   private Date date;
   private String description;
}
public class ToDoPQ {
   ToDoItem getMin(){
    int ans = heap[0];
    return new ToDoItem(ans.date, // okay!
                        ans.description);
   }
}
```

What about this?

```
public class Date { // immutable
    …
}
public class ToDoItem { // immutable (unlike last slide)
    …
}
public class ToDoPQ {
  // a second constructor that uses
  // Floyd's algorithm
  void PriorityQueue(ToDoItem[] items) {
     // what copying should we do?
     …
   }
}
```

What about this?

```
public class Date { // immutable
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public class ToDoPQ {
  // a second constructor that uses
  // Floyd's algorithm
  void PriorityQueue(ToDoItem[] items) {
     // what copying should we do?
     …
   }
}
```

Copy the array, but do not copy the `ToDoItem` or `Date` objects

Homework 5

- You are implementing a graph abstraction
- As provided, **`Vertex`** and **`Edge`** are immutable
  - But **`Collection<Vertex>`** and **`Collection<Edge>`** are not
- You might choose to add fields to **`Vertex`** or **`Edge`** that make them not immutable
  - Leads to more copy-in-copy-out, but that's fine!
- *Or* you might leave them immutable and keep things like "best-path-cost-so-far" in another dictionary (e.g., a **`HashMap`**)

There is more than one good design, but preserve your abstraction

- *Great practice with a key concept in software design*

Randomized Algorithms

- Randomized algorithms (or data structures) rely on some source of randomness
  - Usually a random number generator (RNG)
- True randomness is impossible on a computer
  - We will make do with pseudorandom numbers
- Suppose we only need to flip a coin
  - Can we use the lowest it on the system clock?
  - Does not work well for a sequence of numbers
- Simple method: linear congruential generator
  - Generate a pseudorandom sequence $x_1, x_2, \ldots$ with

$$x_{i+1} = Ax_i \bmod M$$

Linear Congruential Generator

$$x_{i+1} = Ax_i \bmod M$$

- Very sensitive to the choice of A and M
  - Also need to choose x_0 ("the seed")
- For M = 11, A = 7, and x_0 = 1, we get

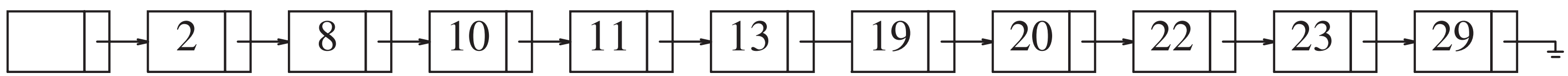
  7,5,2,3,10,4,6,9,8,1,7,5,2,...
- Sequence has a period of M – 1
- Choice of M and A should work to maximize the period
- The Java library's Random uses a slight variation

$$x_{i+1} = (Ax_i + C) \bmod 2^B$$

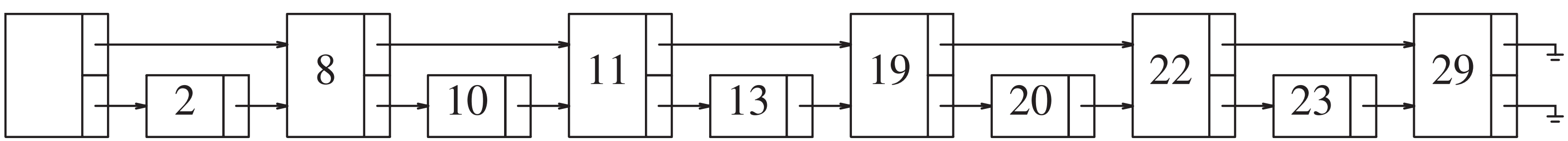
- Using A = 25,214,903,917, C = 13, and B = 48
  - Returns only the high 32 bits

Making sorted linked list better

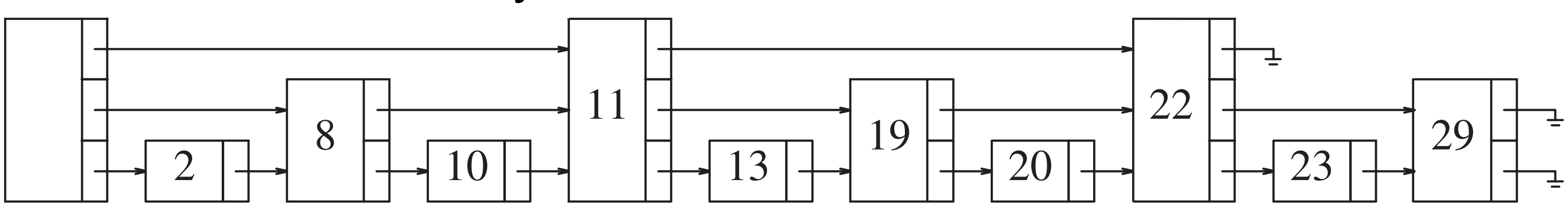
- We can search a sorted array in *O(log n)* using binary search
- But no such luck for a sorted linked list



- We could, however, add additional links
  – Every other node links to the node two ahead of it

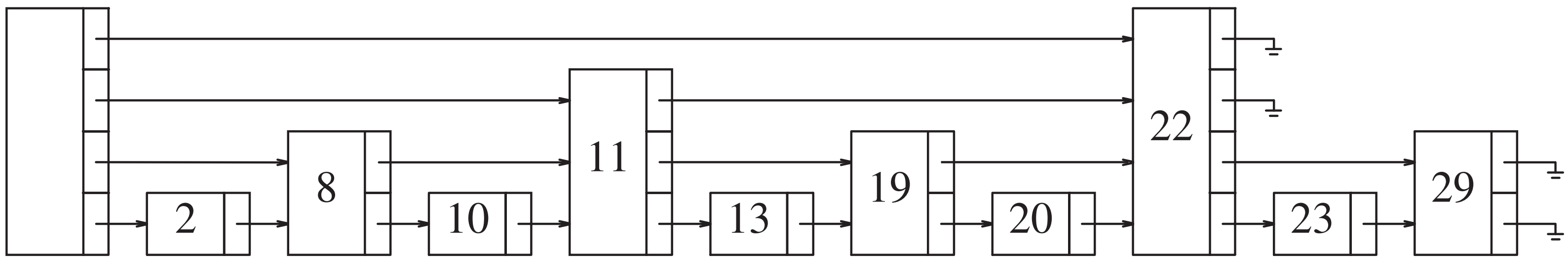


  – Go further: every fourth node links to the node four ahead



To the Logical Conclusion

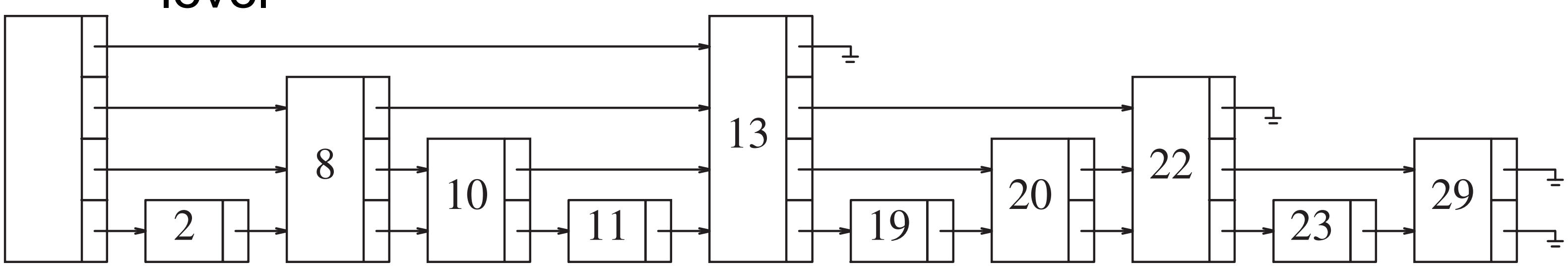
- Take this idea to the logical conclusion
  - Every 2^i th node links to the node 2^i ahead of it



  - Number of links doubles, but now only *log n* nodes are visited in a search!
  - Problem: insert may require completely redoing links
- Define a *level k node* as a node with *k* links
  - We require that the *i*th link in any level *k* node links to the next node with at least *i* levels

Skip List

- Now what does insert look like?
  - Note that in the list with links to nodes 2^i ahead, about 1/2 the nodes are level 1, about a quarter are level 2, …
  - In general, about $1/2^i$ are level *i*
- When we insert, we'll choose the level of the new node randomly according to this probability
  - Flip a coin until it comes up heads, the number of flips is the level



- Operations have expected worst-case running time of *O(log n)*