

## Pre-Announcements (BEAM)

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61B TAs Kevin and Alex and Nicole are here to say in their freetime that they participate in a group called Berkeley Engineering and Mentoring.

- Mentoring for elementary/middle school kids.
- Infosession at 8:00 PM in 145 Dwinelle.
- Also, PIZZA.

# Announcements

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Project 1A is out.

- Very strongly encouraged to work on this project in IntelliJ.
  - Having the ability to visually debug your code is incredibly useful.
  - Having your IDE yell at you about compilation errors while you are writing code is really nice to avoid issues with, for example, generics.
- Autograder is up, but we still want you to write your own tests.
- Tests not graded.
- On part 1B there will be graded tests, so might be worthwhile to write tests just to save yourself some work next week.

LOST section starts tomorrow.

- Tuesdays 5-6 Dwinelle 187 section. Will cover previous week's material.

# CS61B, 2018

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## Lecture 6: Arrays and Lists

- A Last Look at Linked Lists
- Naive Array Lists
- Resizing Arrays
- Generic ALists
- Obscurantism in Java

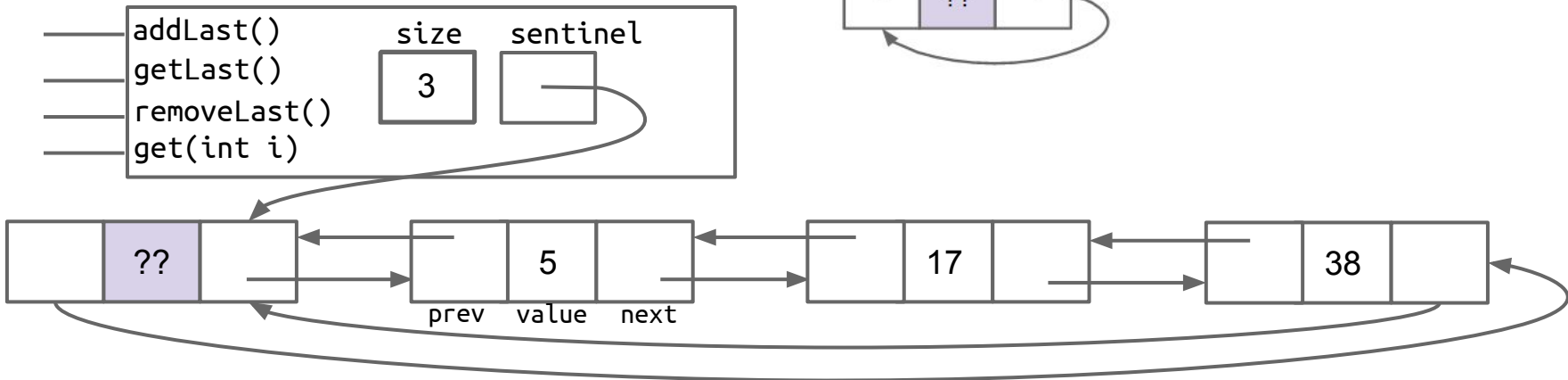
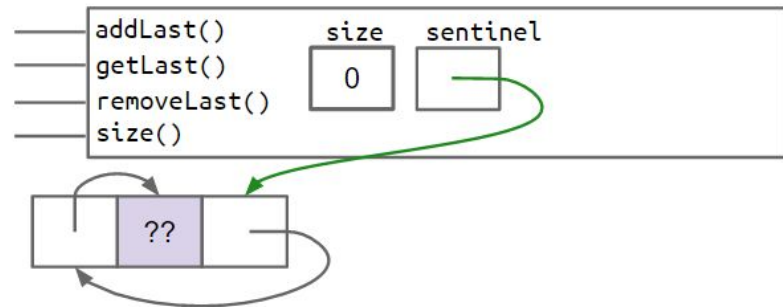


# A Last Look at Linked Lists

# Doubly Linked Lists

Behold. The state of the art as we arrived at in last week's lecture. Through various improvements, we made all of the following operations fast:

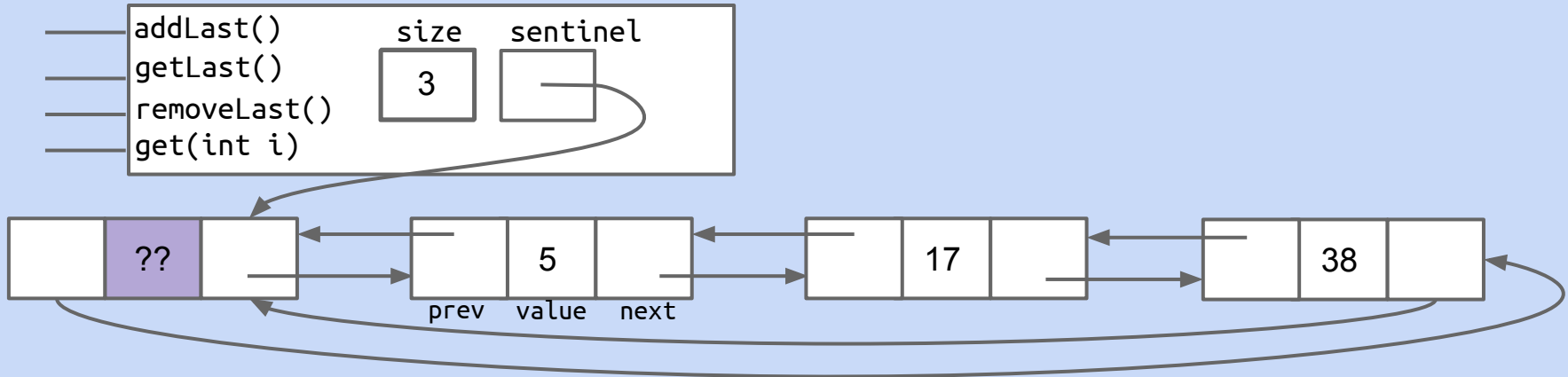
- addFirst, addLast
- getFirst, getLast
- removeFirst, removeLast
- You will build this in project 1A.



## Arbitrary Retrieval

Suppose we added `get(int i)`, which returns the *i*th item from the list.

Why would `get` be slow for long lists compared to `getLast()`? For what inputs?

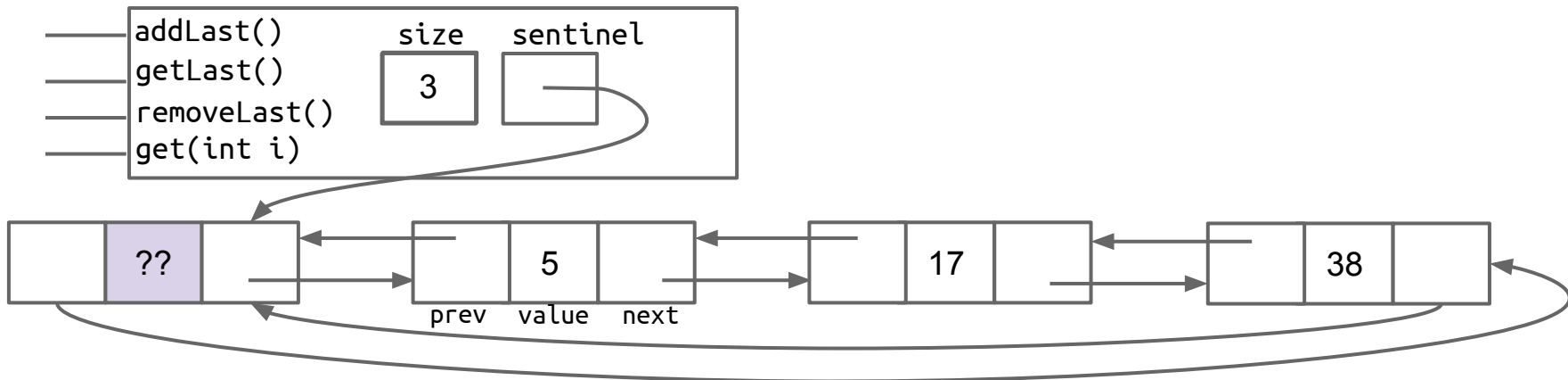


## Arbitrary Retrieval

Suppose we added `get(int i)`, which returns the *i*th item from the list.

Why would `get` be slow for long lists compared to `getLast()`? For what inputs?

- Have to scan to desired position. Slow for any *i* not near the sentinel node.
- How do we fix this?

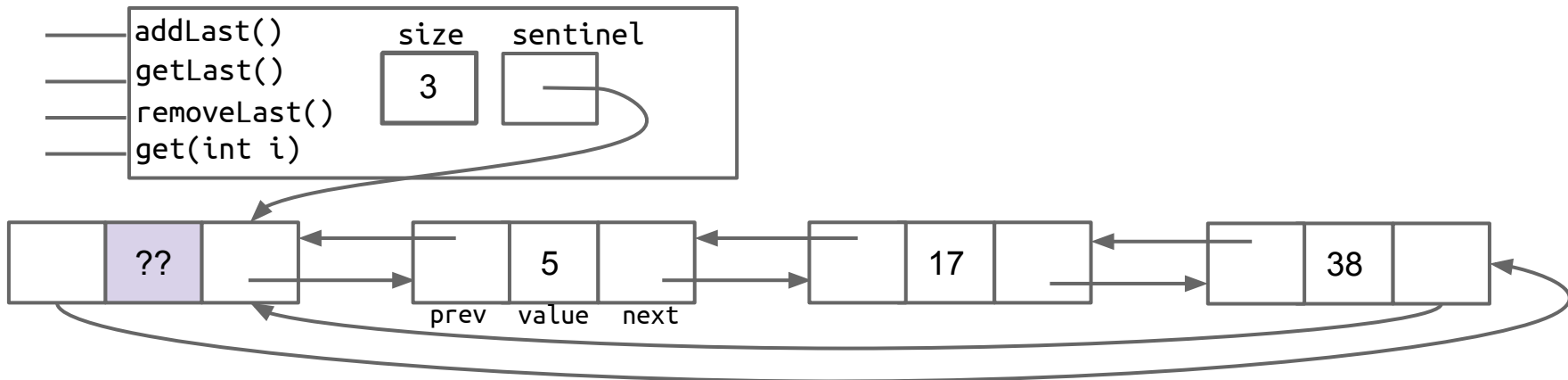


# Arbitrary Retrieval

Suppose we added `get(int i)`, which returns the *i*th item from the list.

Why would `get` be slow for long lists compared to `getLast()`? For what inputs?

- Have to scan to desired position. Slow for any *i* not near the sentinel node.
- Will discuss (much later) sophisticated changes that can speed up lists.
- For now: We'll take a different tack: Using an array instead (no links!).



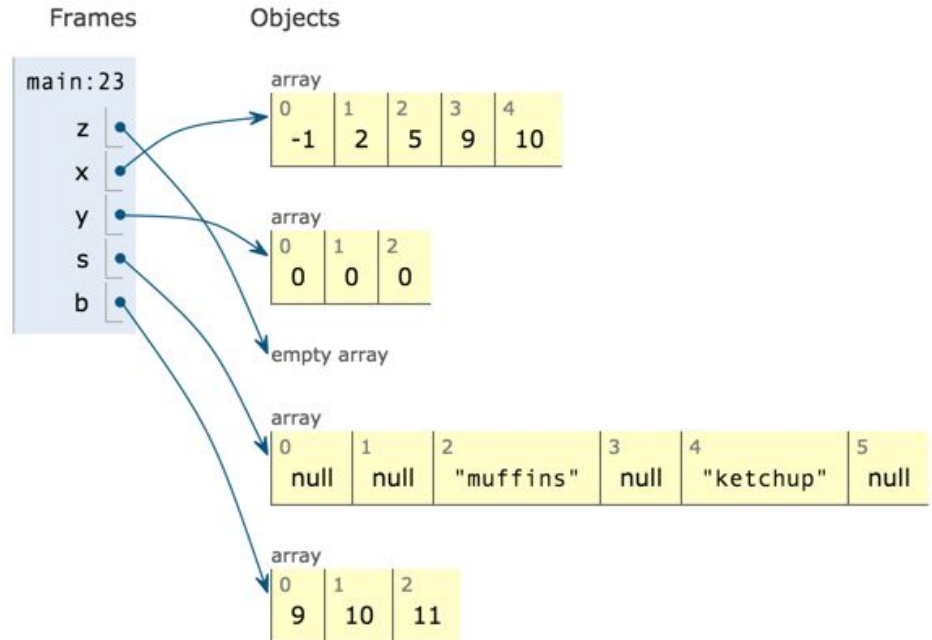


# Naive Array Lists

# Random Access in Arrays

Retrieval from any position of an array is very fast.

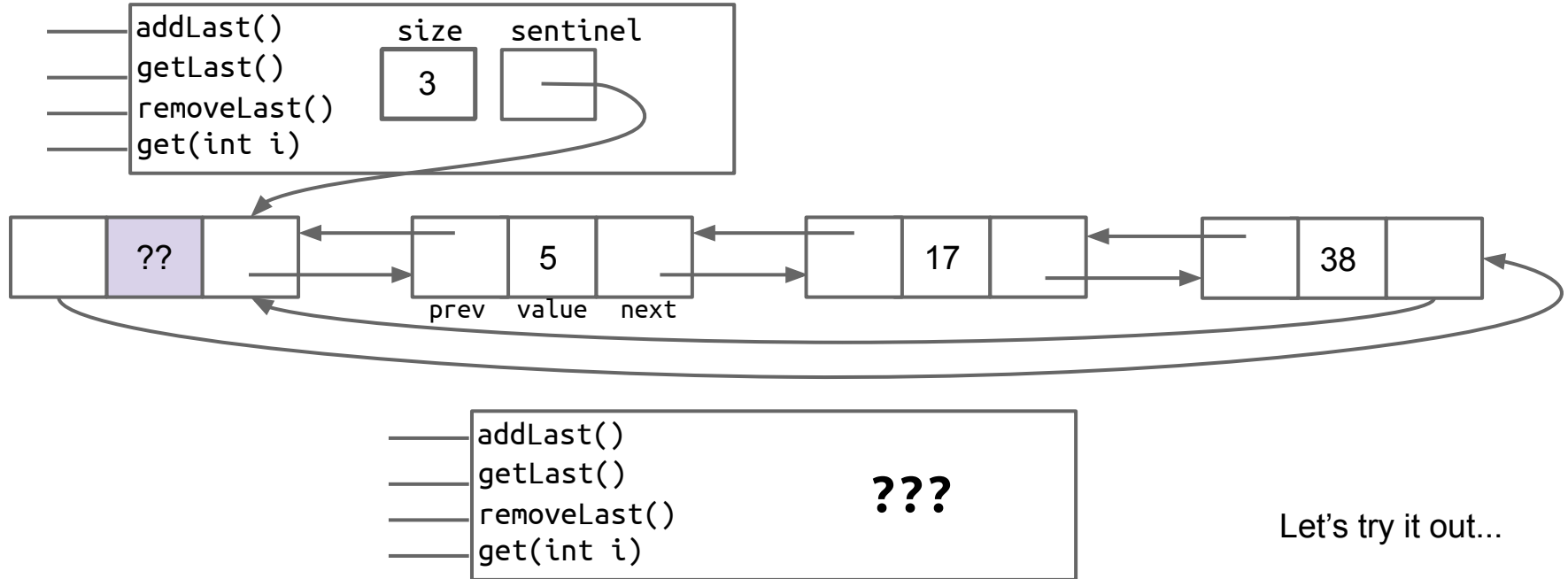
- Independent\* of array size.
- 61C Preview: Ultra fast random access results from the fact that memory boxes are the same size (in bits).



# Our Goal: AList.java


Want to figure out how to build an array version of a list:

- In lecture we'll only do back operations. Project 1A is the front operations.



# Naive AList Code

From last lecture, “things that must be true”.



```
public class AList {
    private int[] items;
    private int size;

    public AList() {
        items = new int[100]; size = 0;
    }

    public void addLast(int x) {
        items[size] = x;
        size += 1;
    }

    public int getLast() {
        return items[size - 1];
    }

    public int get(int i) {
        return items[i];
    }

    public int size() {
        return size;
    }
}
```

## AList Invariants:

- The position of the next item to be inserted is always size.
- size is always the number of items in the AList.
- The last item in the list is always in position size - 1.

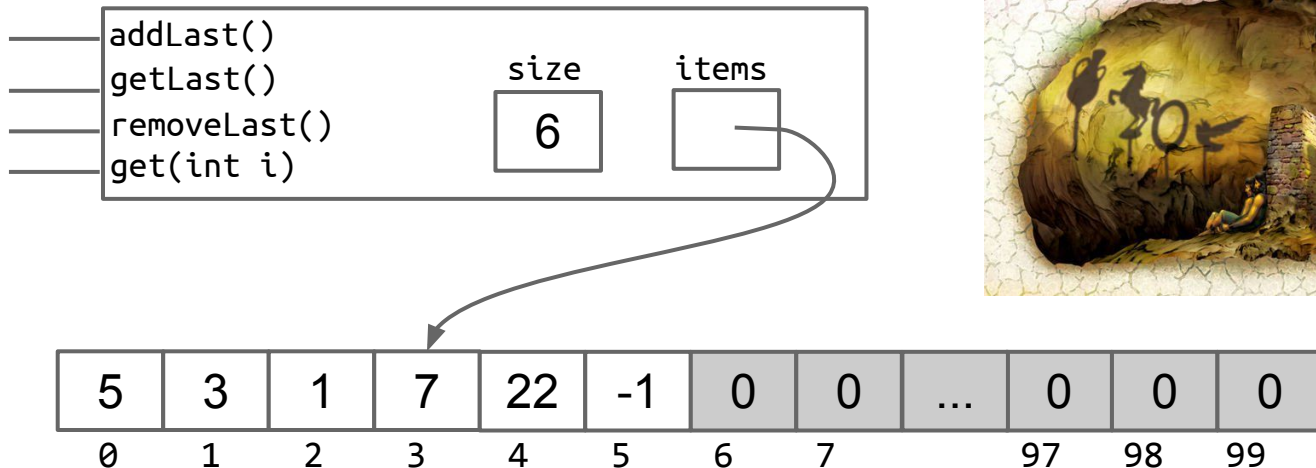
Let's now discuss delete operations.

# The Abstract vs. the Concrete

When we `removeLast()`, which memory boxes need to change? To what?

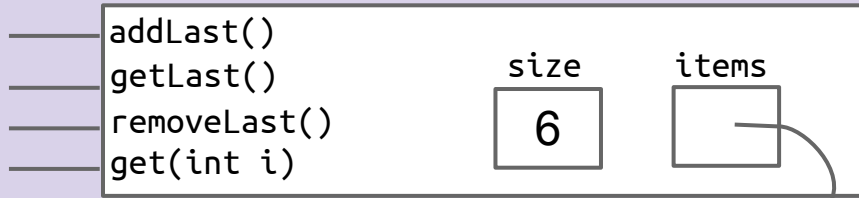
User's mental model:  $\{5, 3, 1, 7, 22, -1\} \rightarrow \{5, 3, 1, 7, 22\}$

Actual truth:

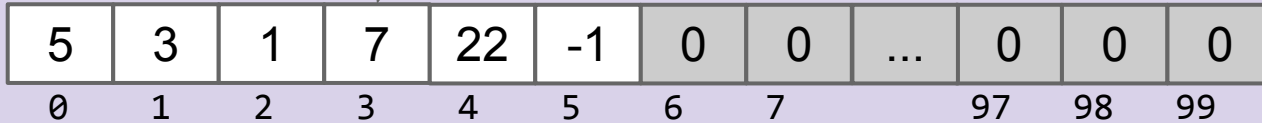


## Deletion: yellkey.com/dark

When we removeLast(), which memory boxes need to change? To what?



- a) `size`
- b) `size` and `items`
- c) `size` and `items[i]` for some `i`
- d) `size`, `items`, and `items[i]` for some `i`
- e) `size`, `items`, and `items[i]` for many different `i`



- The position of the next item to be inserted is always `size`.
- `size` is always the number of items in the AList.
- The last item in the list is always in position `size - 1`.

} AList invariants.

# Naive AList Code

```
public class AList {
    private int[] items;
    private int size;

    public AList() {
        items = new int[100]; size = 0;
    }

    public void addLast(int x) {
        items[size] = x;
        size += 1;
    }

    public int getLast() {
        return items[size - 1];
    }

    public int get(int i) {
        return items[i];
    }

    public int size() {
        return size;
    }
}
```

## AList Invariants:

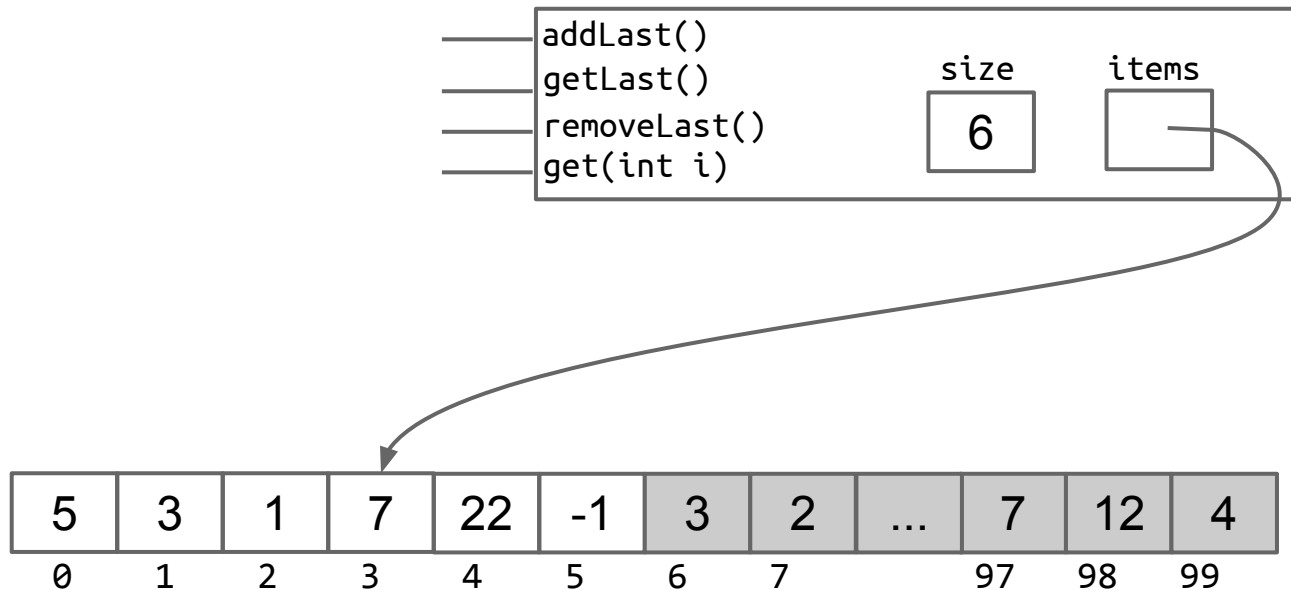
- The position of the next item to be inserted is always `size`.
- `size` is always the number of items in the AList.
- The last item in the list is always in position `size - 1`.

```
public int removeLast() {
    int returnItem = items[size - 1];
    items[size - 1] = 0;
    size -= 1;
    return returnItem;
}
```

Setting deleted item to zero is not necessary to preserve invariants, and thus not necessary for correctness.

# The Mighty AList

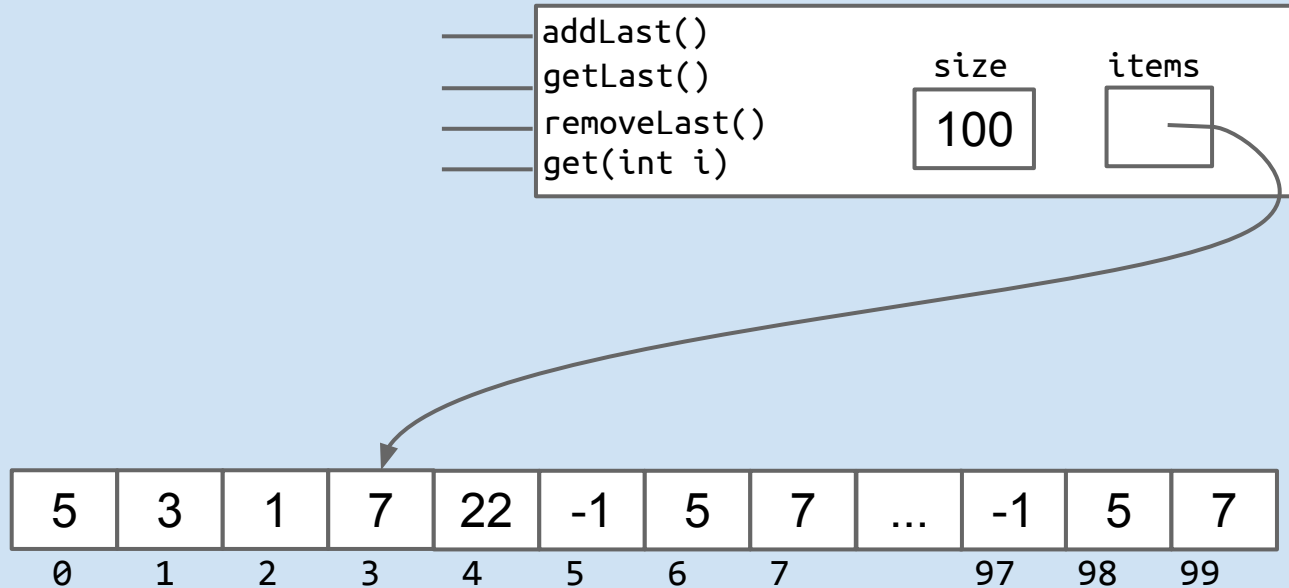
Key Idea: Use some subset of the entries of an array.





# The Mighty (?) AList

Key Idea: Use some subset of the entries of an array.



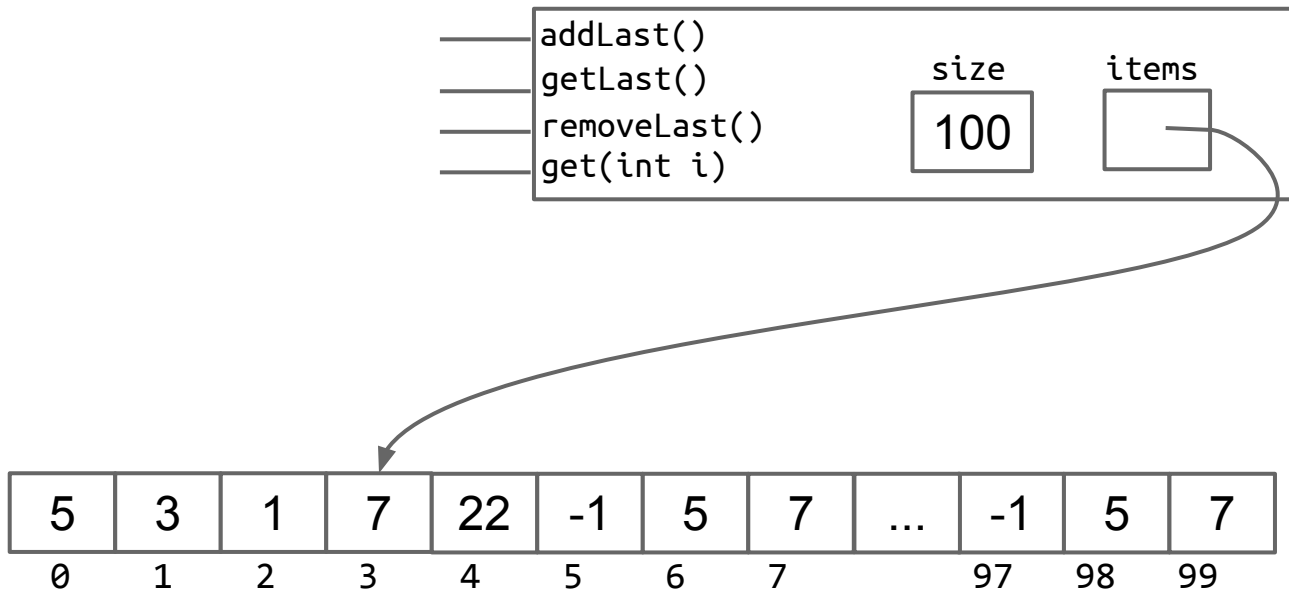
What happens if we insert into the AList above? What should we do about it?

# Resizing Arrays

# Array Resizing

size==items.length

When the array gets too full, e.g. `addLast(11)`, just make a new array:

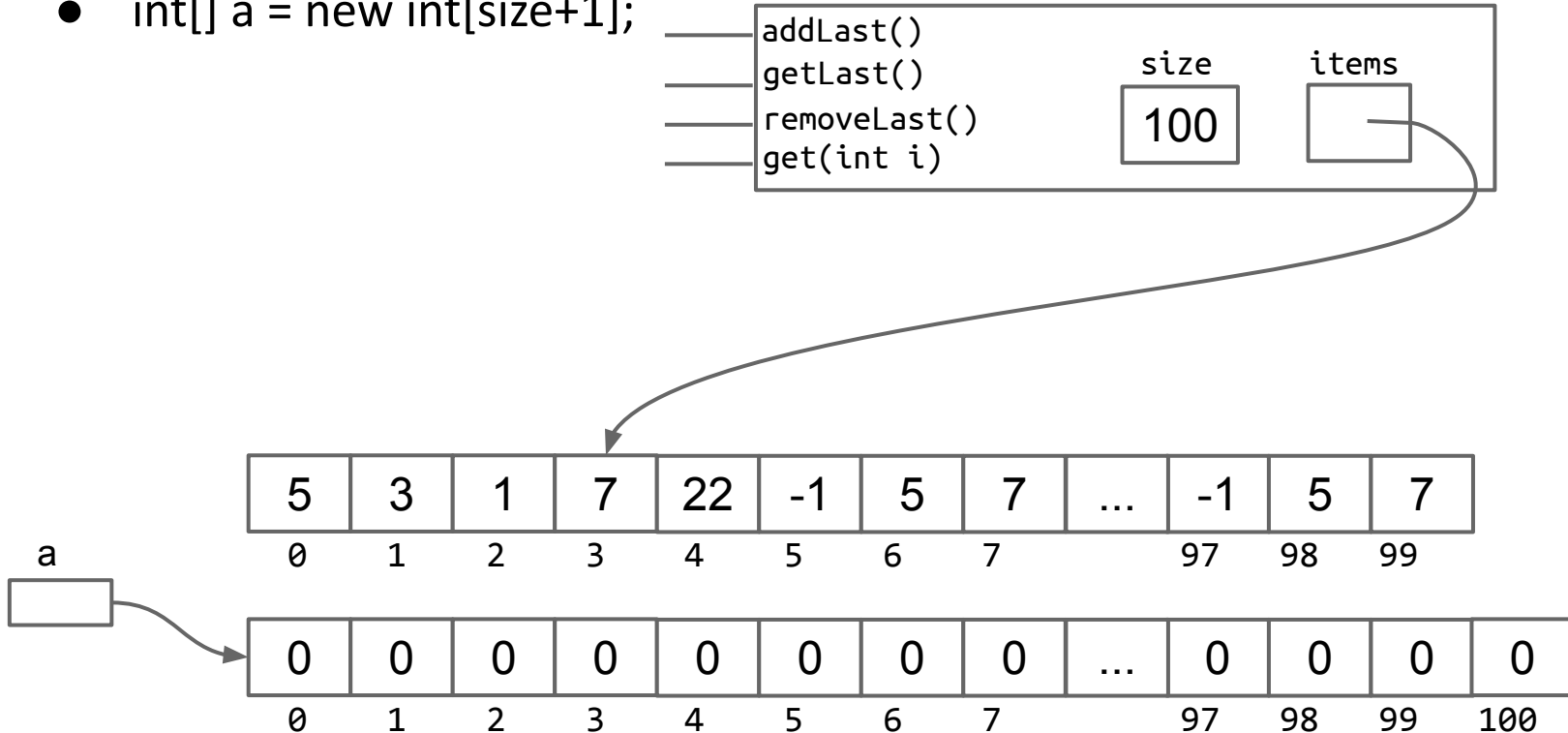


# Array Resizing

size==items.length

When the array gets too full, e.g. `addLast(11)`, just make a new array:

- `int[] a = new int[size+1];`

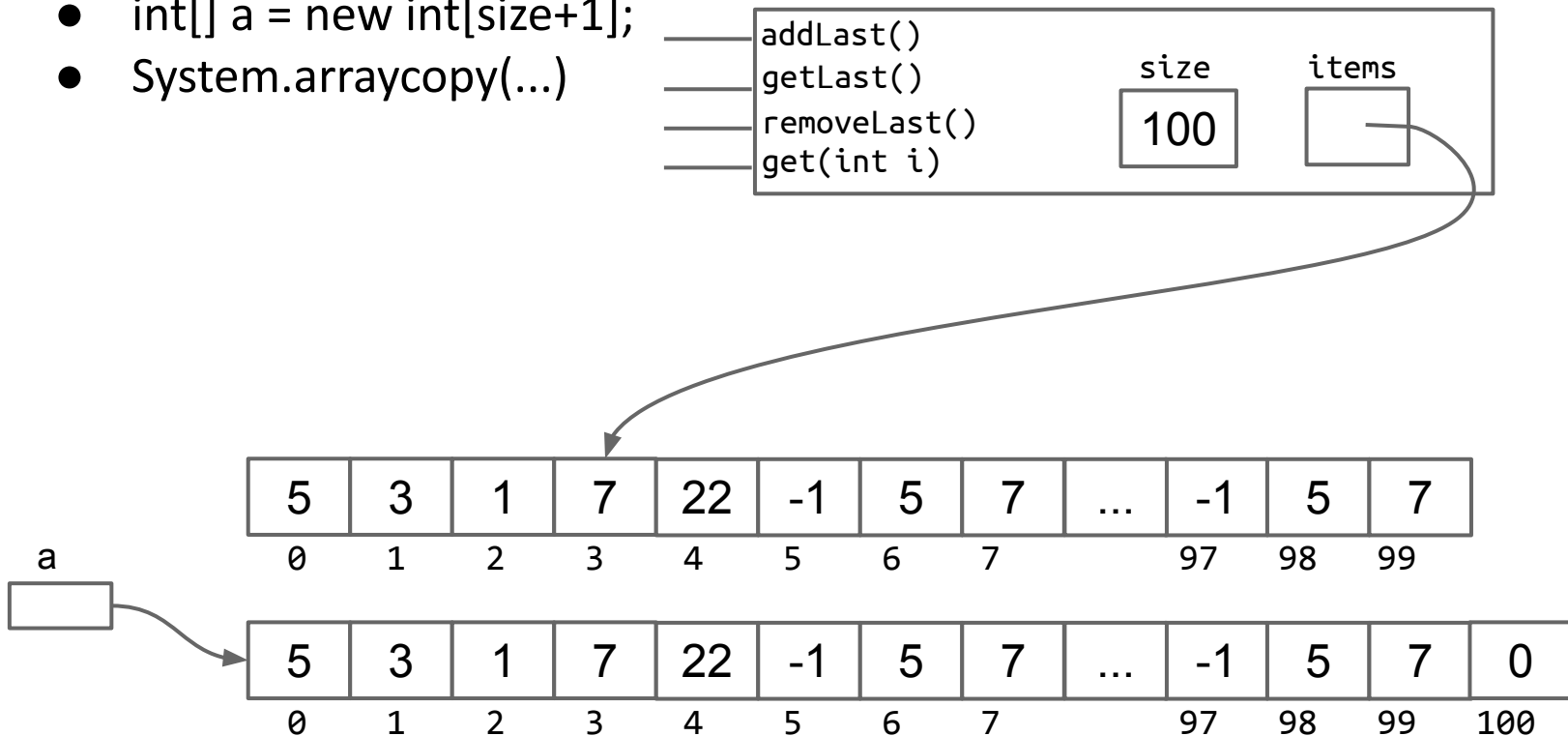


# Array Resizing

size==items.length

When the array gets too full, e.g. `addLast(11)`, just make a new array:

- `int[] a = new int[size+1];`
- `System.arraycopy(...)`

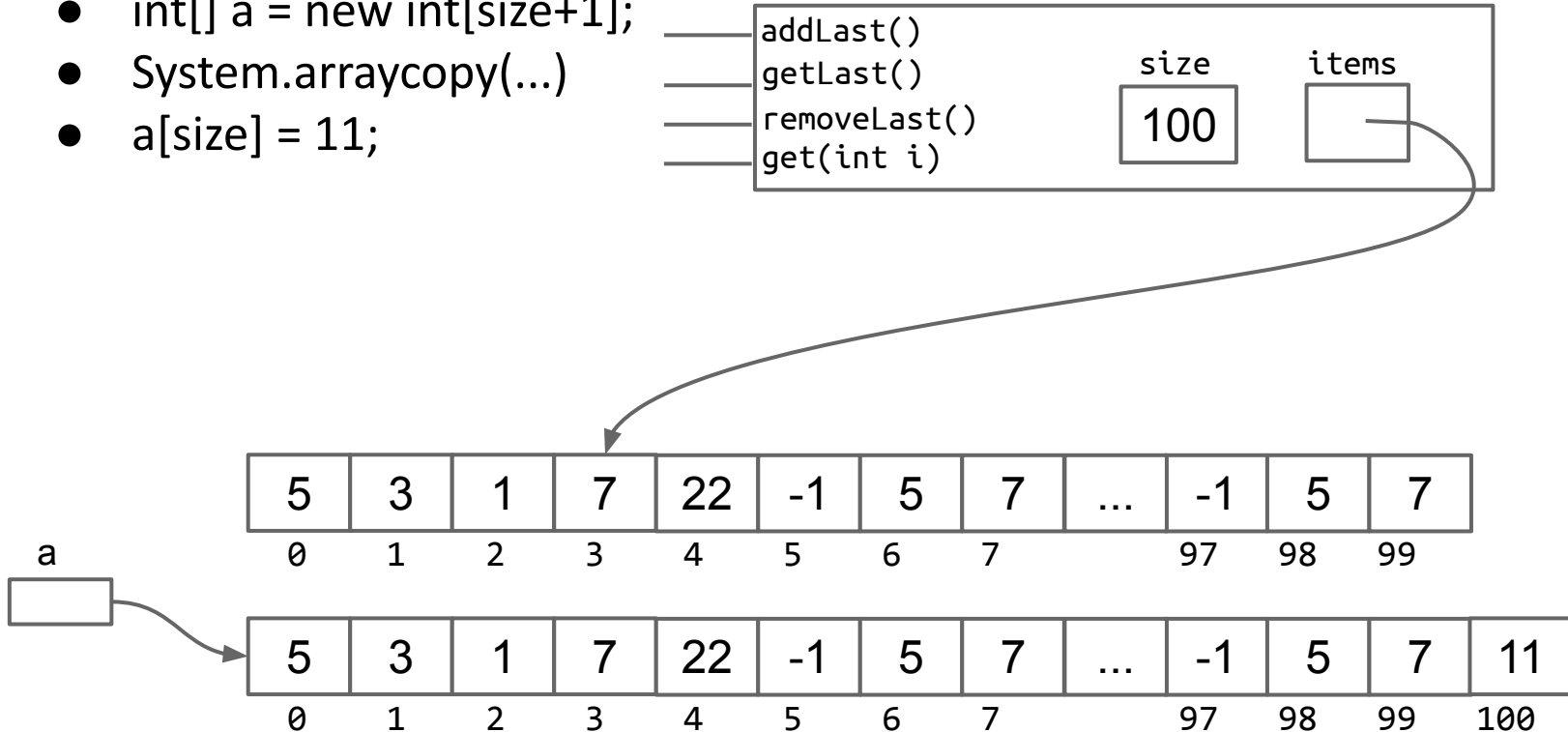


# Array Resizing

size==items.length

When the array gets too full, e.g. `addLast(11)`, just make a new array:

- `int[] a = new int[size+1];`
- `System.arraycopy(...)`
- `a[size] = 11;`

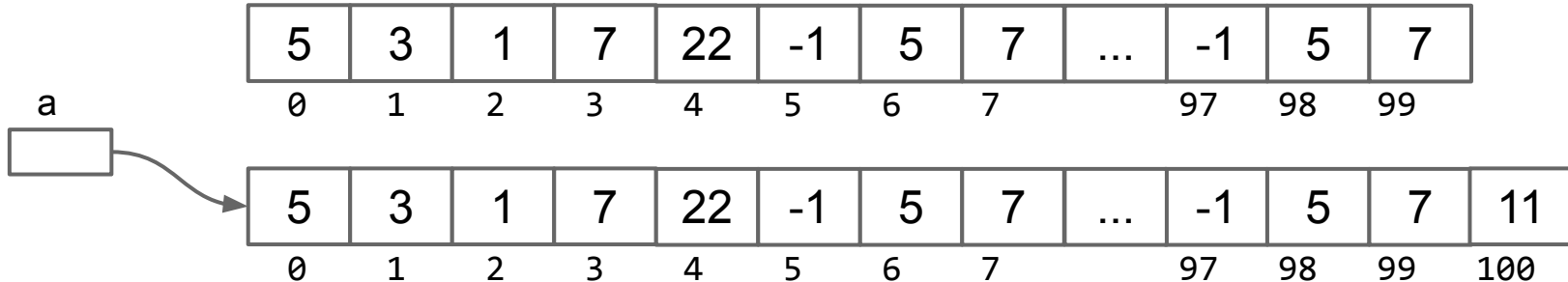


# Array Resizing

size==items.length

When the array gets too full, e.g. `addLast(11)`, just make a new array:

- `int[] a = new int[size+1];`
- `System.arraycopy(...)`
- `a[size] = 11;`
- `items = a; size +=1;`



# Array Resizing

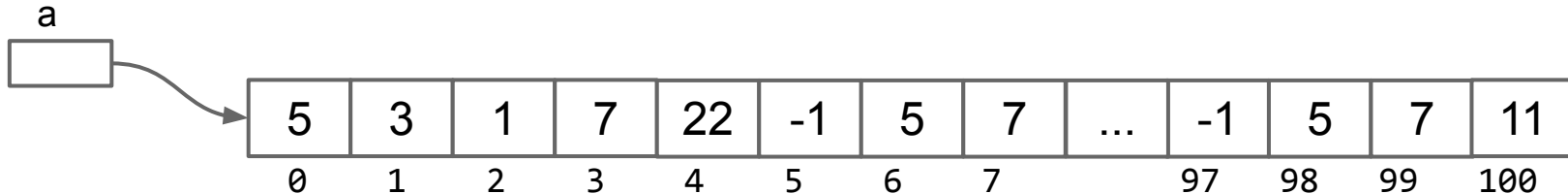
size==items.length

When the array gets too full, e.g. `addLast(11)`, just make a new array:

- `int[] a = new int[size+1];`
- `System.arraycopy(...)`
- `a[size] = 11;`
- `items = a; size +=1;`



We call this process “resizing”





# Implementation

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Let's implement the resizing capability.

- As usual, for those of you watching online, I recommend trying to implement this on your own before watching me do it.
- Starter code is provided in the lists4 study guide if you want to try it out on a computer.

# Resizing Array Code

---

```
public void addLast(int x) {  
    if (size == items.length) {  
        int[] a = new int[size + 1];  
        System.arraycopy(items, 0, a, 0, size);  
        items = a;  
    }  
    items[size] = x;  
    size += 1;  
}
```

Works

```
private void resize(int capacity) {  
    int[] a = new int[capacity];  
    System.arraycopy(items, 0, a, 0, size);  
    items = a;  
}  
  
public void addLast(int x) {  
    if (size == items.length) {  
        resize(size + 1);  
    }  
    items[size] = x;  
    size += 1;  
}
```

Much Better

## Runtime and Space Usage Analysis: yellkey.com/protect

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Suppose we have a full array of size 100. If we call `addLast` two times, how many **total** array memory boxes will we need to create and fill (for just these 2 calls)?

- A. 0
- B. 101
- C. 203
- D. 10,302

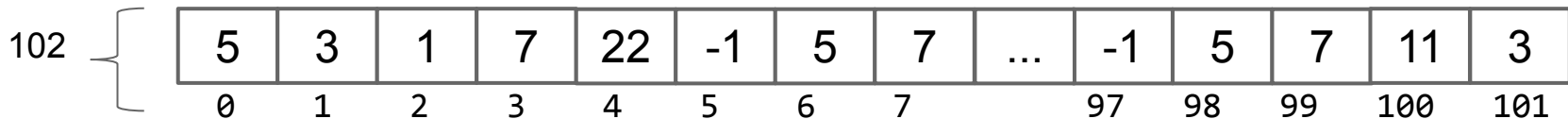
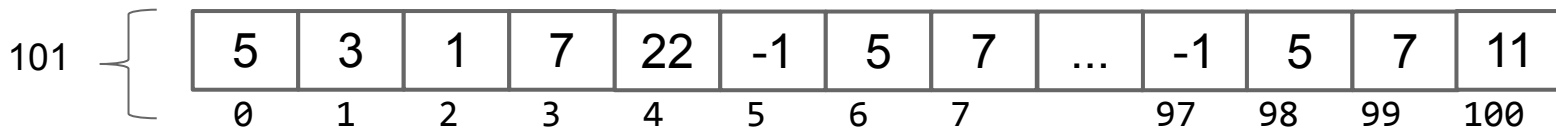
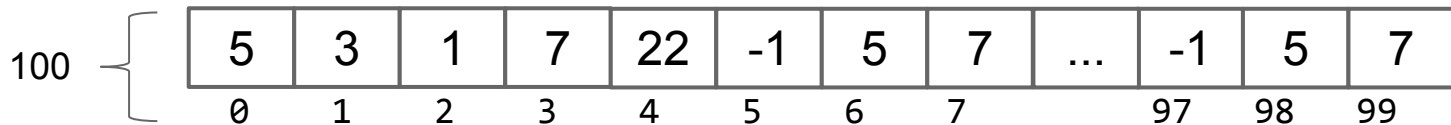
Bonus question: What is the maximum number of array boxes that Java will track at any given time? Assume that “garbage collection” happens immediately when all references to an object are lost.

```
private void resize(int capacity) {  
    int[] a = new int[capacity];  
    System.arraycopy(items, 0, a, 0, size);  
    items = a;  
}  
  
public void addLast(int x) {  
    if (size == items.length) {  
        resize(size + 1);  
    }  
    items[size] = x;  
    size += 1;  
}
```

# Array Resizing

Resizing twice requires us to create and fill 203 total memory boxes.

- Bonus answer: Most boxes at any one time is 203.
- When the second addLast is done, we are left with 102 boxes.



## Runtime and Space Usage Analysis: yellkey.com/protect

---

Suppose we have a full array of size 100. If we call `addLast` until `size = 1000`, roughly how many total array memory boxes will we need to create and fill?

- A. 1,000
- B. 500,000
- C. 1,000,000
- D. 500,000,000,000
- E. 1,000,000,000,000

Bonus question: What is the maximum number of array boxes that Java will track at any given time? Assume that “garbage collection” happens immediately when all references to an object are lost.

```
private void resize(int capacity) {  
    int[] a = new int[capacity];  
    System.arraycopy(items, 0, a, 0, size);  
    items = a;  
}  
  
public void addLast(int x) {  
    if (size == items.length) {  
        resize(size + 1);  
    }  
    items[size] = x;  
    size += 1;  
}
```

# Runtime and Space Usage Analysis

---

Suppose we have a full array of size 100. If we call `addLast` until `size = 1000`, roughly how many total array memory boxes will we need to create and fill?

**B. 500,000**

Going from capacity 100 to 101: 101

From 101 to 102: 102

...

From: 999 to 1000: 1000

```
private void resize(int capacity) {  
    int[] a = new int[capacity];  
    System.arraycopy(items, 0, a, 0, size);  
    items = a;  
}
```

We'll be doing a lot of this after the midterm.

Total array boxes created/copied:  $101 + 102 + \dots + 1000$

Since sum of  $1 + 2 + 3 + \dots + N = N(N+1)/2$ ,  $\text{sum}(101, \dots, 1000)$  is close to 500,000.

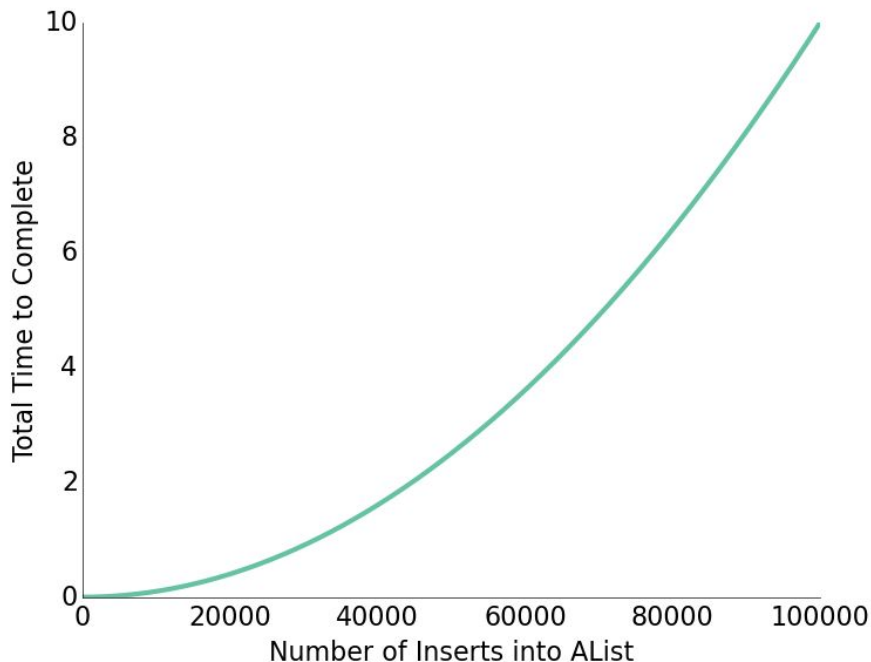
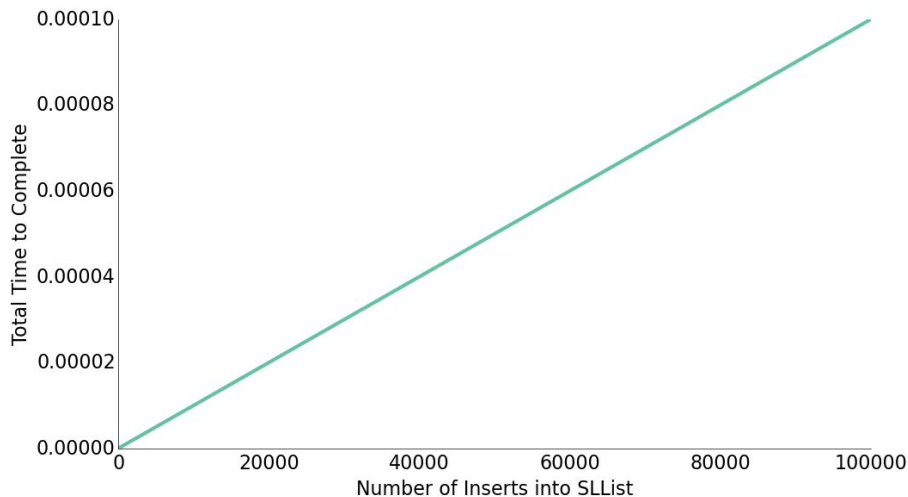
See: <http://mathandmultimedia.com/2010/09/15/sum-first-n-positive-integers>

# Resizing Slowness

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Inserting 100,000 items requires roughly 5,000,000,000 new containers.

- Computers operate at the speed of GHz (due billions of things per second).
- No huge surprise that 100,000 items took seconds.



# Fixing the Resizing Performance Bug

---

How do we fix this?

```
private void resize(int capacity) {  
    int[] a = new int[capacity];  
    System.arraycopy(items, 0, a, 0, size);  
    items = a;  
}  
  
public void addLast(int x) {  
    if (size == items.length) {  
        resize(size + 1);  
    }  
    items[size] = x;  
    size += 1;  
}
```



## (Probably) Surprising Fact

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Geometric resizing is much faster: Just how much better will have to wait.

```
public void addLast(int x) {  
    if (size == items.length) {  
        resize(size + RFACTOR);  
    }  
    items[size] = x;  
    size += 1;  
}
```

← Unusably bad.

Great performance. →

This is how the Python list is implemented.

```
public void addLast(int x) {  
    if (size == items.length) {  
        resize(size * RFACTOR);  
    }  
    items[size] = x;  
    size += 1;  
}
```

## Performance Problem #2

---

Suppose we have a very rare situation occur which causes us to:

- Insert 1,000,000,000 items.
- Then remove 990,000,000 items.

Our data structure will handle this spike of events as well as it could, but afterwards there is a problem.

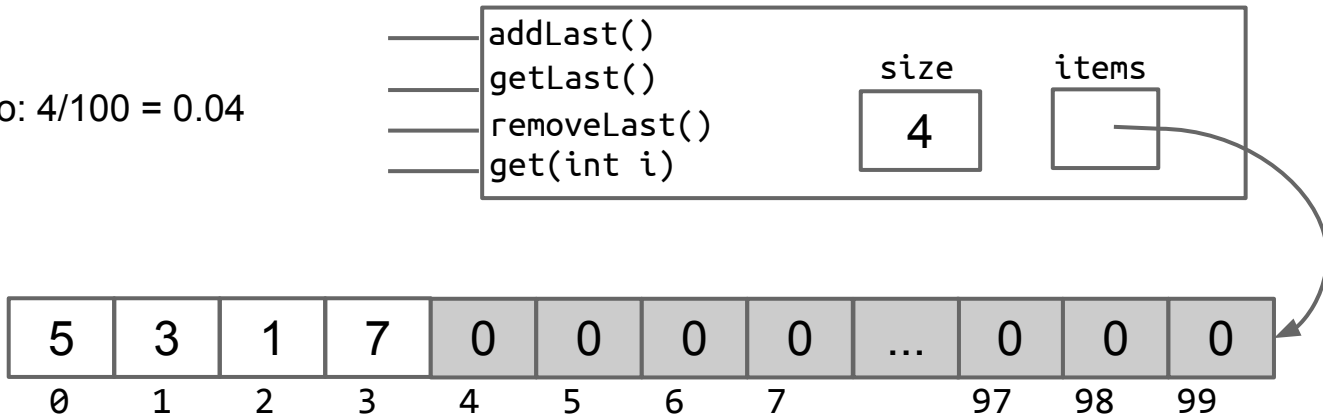
- What is the problem?

# Memory Efficiency

An AList should not only be efficient in time, but also efficient in space.

- Define the “usage ratio”  $R = \text{size} / \text{items.length}$ ;
- Typical solution: Half array size when  $R < 0.25$ .
- More details in a few weeks.

Usage ratio:  $4/100 = 0.04$



Later we will consider tradeoffs between time and space efficiency for a variety of algorithms and data structures.

# Generic ALists

# Generic ALists (similar to generic SLists)

```
public class AList {
    private int[] items;
    private int size;

    public AList() {
        items = new int[8];
        size = 0;
    }

    private void resize(int capacity) {
        int[] a = new int[capacity];
        System.arraycopy(items, 0,
                        a, 0, size);

        items = a;
    }

    public int get(int i) {
        return items[i];
    }
    ...
}
```

```
public class AList<Glorp> {
    private Glorp[] items;
    private int size;

    public AList() {
        items = (Glorp []) new Object[8];
        size = 0;
    }

    private void resize(int cap) {
        Glorp[] a = (Glorp []) new Object[cap];
        System.arraycopy(items, 0,
                        a, 0, size);

        items = a;
    }

    public Glorp get(int i) {
        return items[i];
    }
    ...
}
```

# Generic ALists (similar to generic SLists)

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public class AList<Glorp> {  
    private Glorp[] items;  
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    public AList() {  
        items = (Glorp []) new Object[8];  
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    }  
  
    private void resize(int cap) {  
        Glorp[] a = (Glorp []) new Object[cap];  
        System.arraycopy(items, 0,  
                           a, 0, size);  
        items = a;  
    }  
  
    public Glorp get(int i) {  
        return items[i];  
    }  
    ...  
}
```

When creating an array of references to Glorps:

- `(Glorp []) new Object[cap];`
- Causes a compiler warning, which you should ignore.

Why not just `new Glorp[cap];`

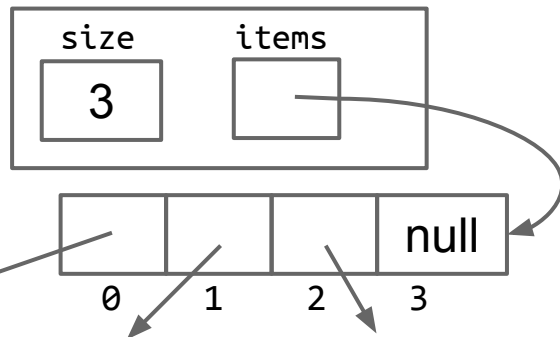
- Will cause a “generic array creation” error.
- Will discuss in a few weeks.

# Nulling Out Deleted Items

Unlike integer based ALists, we actually want to null out deleted items.

- Java only destroys unwanted objects when the last reference has been lost.
- Keeping references to unneeded objects is sometimes called loitering.
- Save memory. Don't loiter.

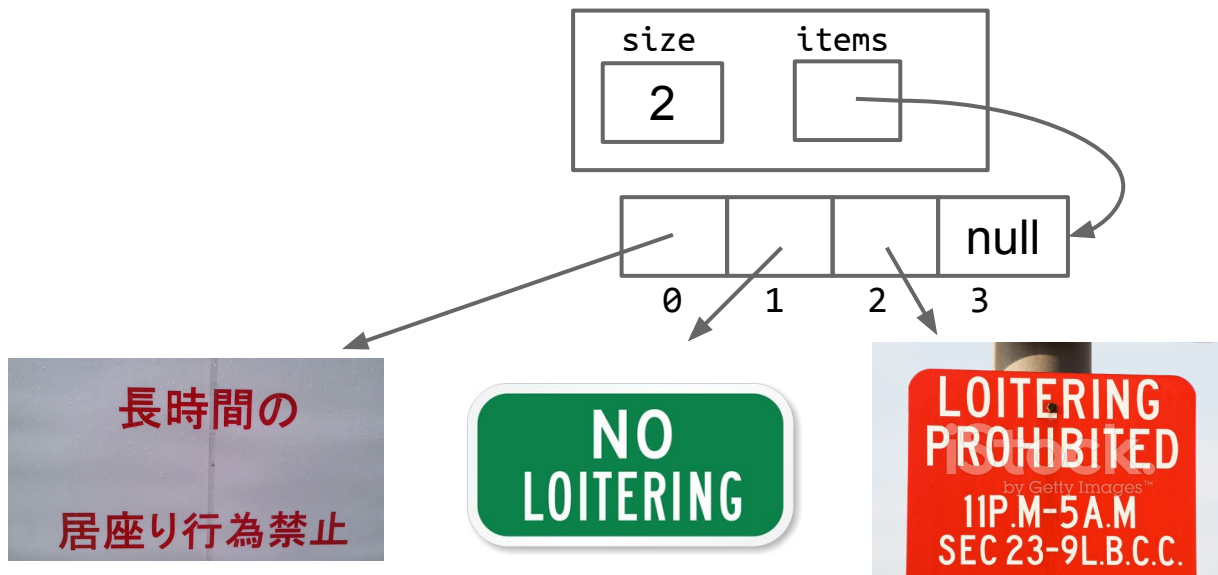
```
public Glorp deleteBack() {  
    Glorp returnItem = getBack();  
    items[size - 1] = null;  
    size -= 1;  
    return returnItem;  
}
```



# Loitering Example

Changing size to 2 yields a correct AList.

- But memory is wasted storing a reference to the red sign image.



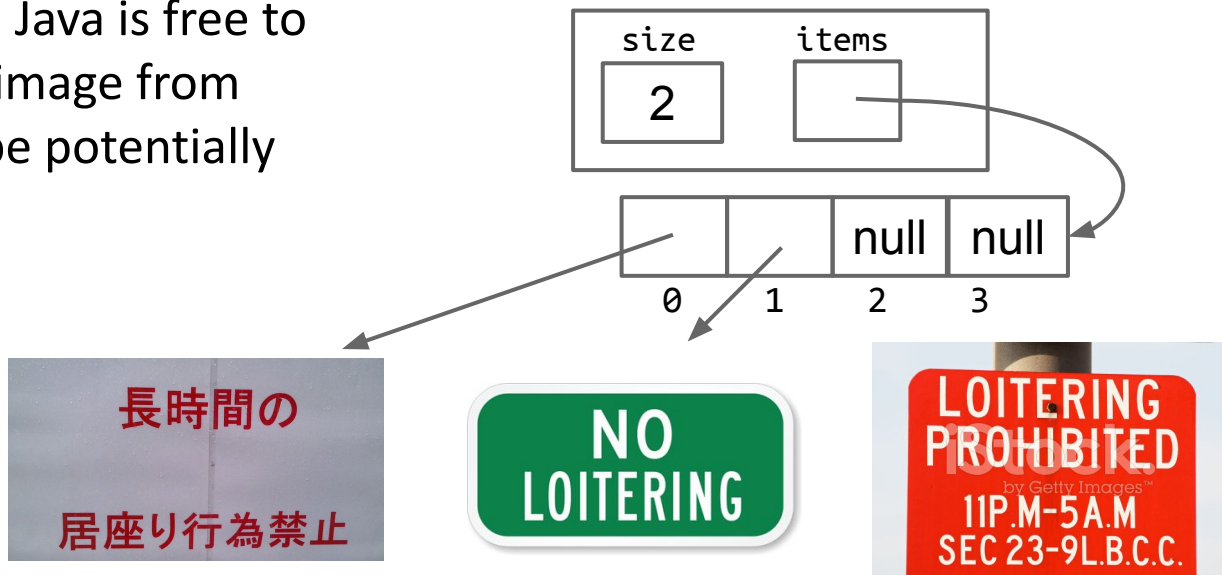


## Loitering Example

Changing size to 2 yields a correct AList.

- But memory is wasted storing a reference to the red sign image.

By nulling out items[2], Java is free to destroy the unneeded image from memory, which could be potentially megabytes in size.

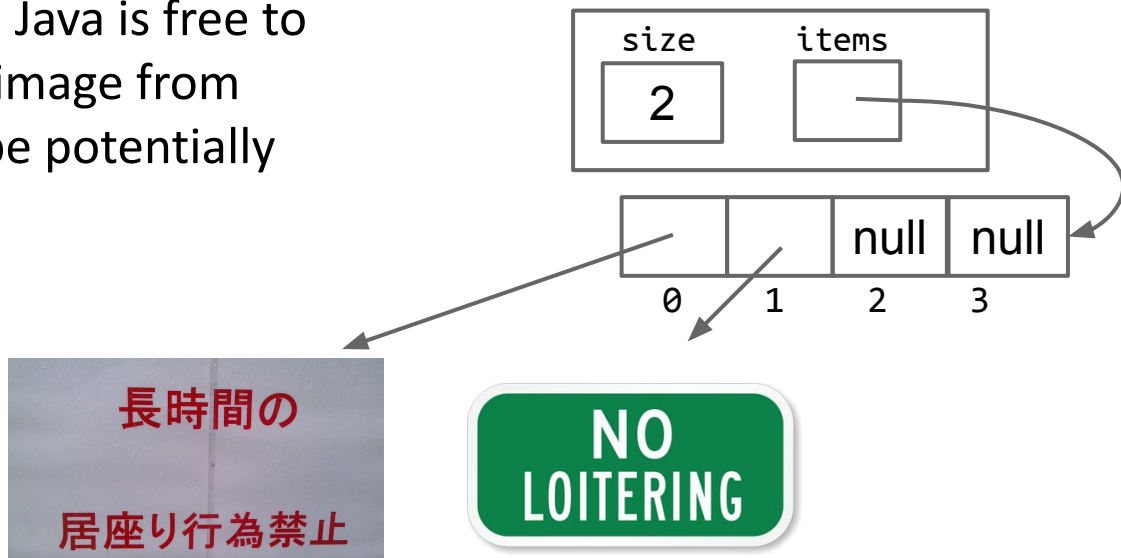


## Loitering Example

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# Obscurantism in Java

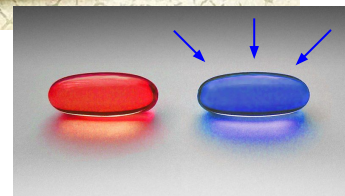
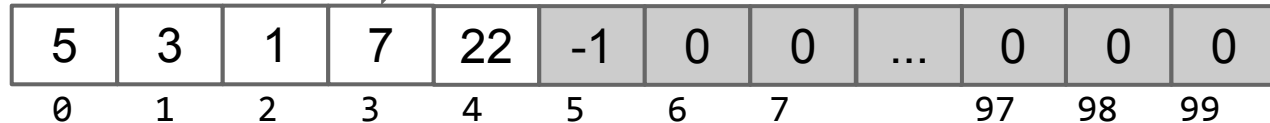
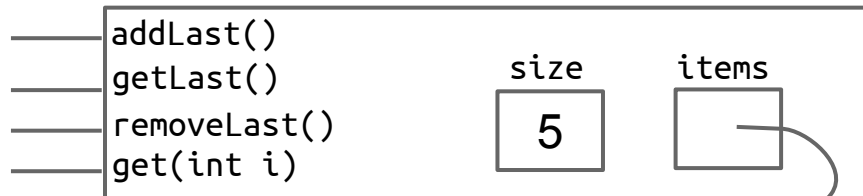
# One last thought: Obscurantism in Java

We talk of “layers of abstraction” often in computer science.

- We also rely on obscurantism. The user of a class does not and should not know how it works.

**User's mental model:**  $\{5, 3, 1, 7, 22, -1\} \rightarrow \{5, 3, 1, 7, 22\}$

**Actual truth:**

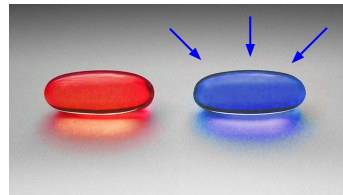


# One last thought: Obscurantism in Java

---

We talk of “layers of abstraction” often in computer science.

- We also rely on obscurantism. The user of a class does not and should not know how it works.
  - The Java language allows you to enforce this with ideas like **private**!
- A good programmer obscures details from themselves, even within a class.
  - Example: `addFirst` and `resize` should be written totally independently. You should not be thinking about the details of one method while writing the other. Simply trust that the other works.
  - Breaking programming tasks down into small pieces (especially functions) helps with this greatly!
  - Through judicious use of testing, we can build confidence in these small pieces, as we'll see in the next lecture.



# Citations

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Hanging Containers:

[http://www.portcalls.com/wp-content/uploads/2012/04/hanging\\_containers1.jpg](http://www.portcalls.com/wp-content/uploads/2012/04/hanging_containers1.jpg)

Loitering:

[http://i.istockimg.com/file\\_thumbview\\_approve/19711163/6/stock-photo-19711163-red-loitering-prohibited-sign.jpg](http://i.istockimg.com/file_thumbview_approve/19711163/6/stock-photo-19711163-red-loitering-prohibited-sign.jpg)

<http://images.mysecuritysign.com/img/lg/K/No-Loitering-Sign-K-5418.gif>

[http://3.bp.blogspot.com/-NV3y2NQDFy0/UAAXB5gINoI/AAAAAAAAALi8/F\\_bM4-dmsm4/s1600/DVC00575.JPG](http://3.bp.blogspot.com/-NV3y2NQDFy0/UAAXB5gINoI/AAAAAAAAALi8/F_bM4-dmsm4/s1600/DVC00575.JPG)

Red pill/blue pill: [https://en.wikipedia.org/wiki/Red\\_pill\\_and\\_blue\\_pill](https://en.wikipedia.org/wiki/Red_pill_and_blue_pill)