CSE 331

Software Design & Implementation

Topic: Rep. Exposure; Abstraction Functions

Discussion: Any plans for the July 4th holiday?

Reminders

- Tomorrow is a national holiday!
  - Won't hold Tanay's office hours
- Slight delay in HW2 grading

Upcoming Deadlines

• Prep. Quiz: HW3	due Monday (7/3)
• HW3	due Thursday (7/6)

Last Time...

- Abstract Data Types
- ADTs in Java
    - overview
    - abstract state
    - creators
    - observers
    - producers
    - mutators
- Representation Invariants

Today's Agenda

- Representation Exposure
- Abstraction Functions
- Intro to Testing

Recap: ADTs and RIs

Abstract Data Type (ADT)

ADT abstracts from the *organization* to *meaning* of data

- details of data structures are hidden from the client
- allows us to *delay* decisions about data structures

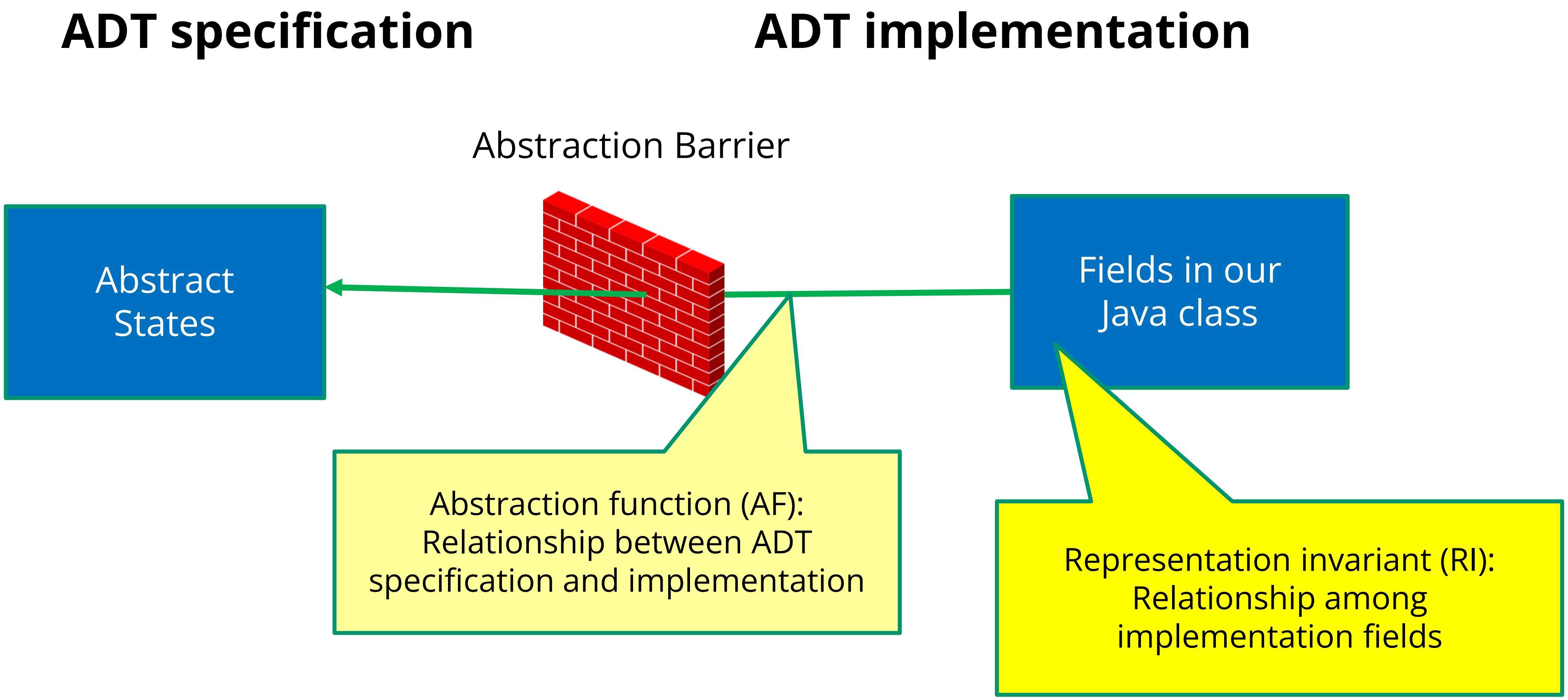
Often best to start your design by designing data

- first, what **operations** will be permitted on the data (for clients)
- next, decide how data be **organized** (data structures)
    - see CSE 332 & CSE 344
- lastly, write the **code**

Then use **reasoning** to verify the operations are correct

- two intellectual tools are helpful for this...

Data abstraction outline



Connecting implementations to specs

For implementers / debuggers / maintainers of the implementation:

Representation Invariant: maps Object → boolean

- defines the set of valid concrete values
- **no object should *ever* violate the rep invariant**
  - such an object has no useful meaning

Abstraction Function: maps Object → abstract state

- we'll discuss this later today!

Example: Circle 2

```
/** Represents a mutable circle in the plane. For example,
  * it can be a circle with center (0,0) and radius 1. */
public class Circle {

  // Rep invariant: center != null and edge != null
  //   and !center.equals(edge)
  private Point center, edge;

  // Abstraction function:
  // AF(this) = a circle with center at this.center
  //   and radius this.center.distanceTo(this.edge)

  //  ...
}
```

Example: Polynomial 2

```
/** An immutable polynomial with integer coefficients.
  * Examples include 0, 2x, and x + 3x^2 + 5x. */
public class IntPoly {

  // Rep invariant: terms != null and
  //     no two terms have the same degree and
  //     terms is sorted in descending order by degree
  private final LinkedList<IntTerm> terms;

  // Abstraction function:
  // AF(this) = sum of monomials in this.terms

  //  ... coeff, degree, etc.
```

Defensive Programming with ADTs

Checking rep invariants

Should you write code to check that the rep invariant holds?

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- Yes, if it's inexpensive [same as preconditions]

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- Yes, for debugging [even when it's expensive]

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– Yes, if it's inexpensive [same as preconditions]

– Yes, for debugging [even when it's expensive]

Often hard to justify turning the safety checks off…

- make the code run faster (rare)
- make the code easier to understand

Checking rep invariants

Should you write code to check that the rep invariant holds?

- Yes, if it's inexpensive [same as preconditions]

- Yes, for debugging [even when it's expensive]

Often hard to justify turning the safety checks off…

- make the code run faster (rare)
- make the code easier to understand

Where should you check that the rep invariant holds?

Example: String

```
public class String {

    // Rep invariant: arr != null
    private char[] arr;

    // Some operations supported by the ADT
    public bool isEmpty() { return arr.length() == 0; }
    public bool startsWith(char c) { return arr[0] == c; }
    public void yikes() {  arr = null;  }
}
```

Checking rep invariants

Since representation invariants hold before and after each method in the public specification, we can introduce a great debugging technique:

Catch bugs by implementing and using a function to check the rep. invariant

Note: only needed for public methods.

Example: CharSet ADT

```
// Overview: A CharSet is a finite mutable set of Characters

// @effects: creates a fresh, empty CharSet
public CharSet() {…}

// @modifies: this
// @effects: this changed to this + {c}
public void insert(Character c) {…}

// @modifies: this
// @effects: this changed to this - {c}
public void delete(Character c) {…}

// @return: true iff c is in this set
public boolean member(Character c) {…}

// @return: cardinality of this set
public int size() {…}
```

Example: CharSet Representation

```
// Rep invariant: elts != null and
//        elts has no nulls and no dups
private List<Character> elts;
```

Checking the rep invariant

How do we check whether this invariant holds?

```
public void delete(Character c) {

    elts.remove(c);  // removes 0 or 1 copies of c

}
```

Checking the rep invariant

Rule of thumb: check on entry *and* on exit (why?)

```
public void delete(Character c) {
  checkRep();
  elts.remove(c);  // removes 0 or 1 copies of c
  checkRep();
}

// Verify that elts contains no nulls or dups
private void checkRep() {
    assert elts != null;
    for (int i = 0; i < elts.size(); i++) {
        assert elts.get(i) != null;
        assert elts.indexOf(elts.get(i)) == i;
    }
}
```

Practice *defensive programming*

- Question is not: will you make mistakes? You will.
- Question is: will you **catch** those mistakes before users do?

- Write and incorporate code designed to catch the errors you make
  - check rep invariant on entry (of mutators)
  - check rep invariant on exit (of mutators and creators)
  - check preconditions (don't trust other programmers)
  - check postconditions (don't trust yourself either)

- Checking the rep invariant helps *discover* errors while testing
- Reasoning about the rep invariant helps *discover* errors while coding

Practice *defensive programming*

Focus on defensive programming against **subtle bugs**

- obvious bugs (e.g., crashing every time) will be caught in testing
- subtle bugs that only occasionally cause problems can sneak out
- be especially defensive against (and scared of) these

Listing the elements of a CharSet

Consider adding the following method to **`CharSet`**

```
// returns: a List containing the members of this
public List<Character> getElts();
```

Consider this implementation:

```
public List<Character> getElts() { return elts; }
```

Does this implementation preserve the rep invariant?

Can't say!

Representation exposure

Consider this client code (outside the **`CharSet`** implementation):

```
CharSet s = new CharSet();
Character a = new Character('a');

s.insert(a);
List<Character> elts = s.getElts();
s.delete(a);
bool isMember = s.member(a);
```

We expect that **`isMember`** is false.

Representation exposure

Consider this client code (outside the **`CharSet`** implementation):

```
CharSet s = new CharSet();
Character a = new Character('a');

s.insert(a);
s.insert(a);
List<Character> elts = s.getElts();
s.delete(a);
bool isMember = s.member(a);
```

We *still* expect that **`isMember`** is false.

Representation exposure

Consider this client code (outside the **`CharSet`** implementation):

```
CharSet s = new CharSet();
Character a = new Character('a');

s.insert(a);
s.insert(a);
List<Character> elts = s.getElts();
s.delete(a);
bool isMember = s.member(a);
```

We *still* expect that **`isMember`** is false.

Representation exposure

Consider this client code (outside the **CharSet** implementation):

```
CharSet s = new CharSet();
Character a = new Character('a');

s.insert(a);
List<Character> elts = s.getElts();
elts.add(a); // yikes!
s.delete(a);
bool isMember = s.member(a);
```

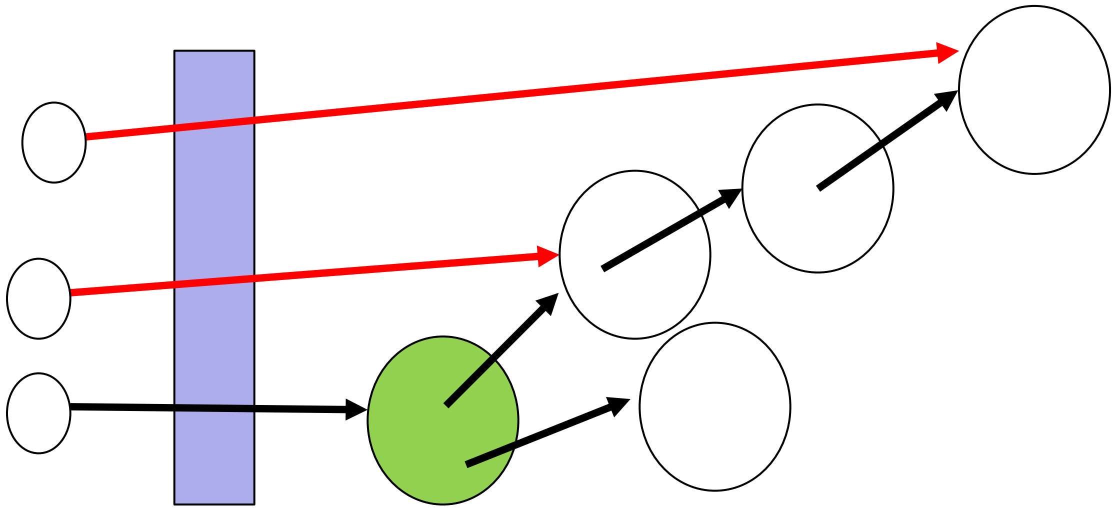
- Suddenly, we see that **isMember** is true.
- Representation exposure is allowing clients to access the internal rep

Avoiding representation exposure

- *Understand* what representation exposure is
- *Design* ADT implementations to make sure it doesn't happen
- Treat rep exposure as a bug: *fix* your bugs
  - absolutely must avoid in libraries with many clients
- *Test* for it with *adversarial clients:*
  - pass values to methods and then mutate them
  - mutate values returned from methods

`private` is not enough

- Making fields **`private`** does *not* suffice to prevent rep exposure
  - see our example
  - issue is ***aliasing of mutable data outside the abstraction***



- So **`private`** is a hint to you: no aliases outside abstraction to references to mutable data reachable from **`private`** fields
- Three general ways to avoid representation exposure…

Avoiding rep exposure (way #1)

- One way to avoid rep exposure is to make copies of all data that cross the abstraction barrier
  - Copy in [parameters that become part of the implementation]
  - Copy out [results that are part of the implementation]

- Examples of copying (assume **`Point`** is a mutable ADT):

```
class Line {
    private Point s, e;
    public Line(Point s, Point e) {
        this.s = new Point(s.x,s.y);
        this.e = new Point(e.x,e.y);
    }
    public Point getStart() {
        return new Point(this.s.x,this.s.y);
    }
    …
```

Avoiding rep exposure (way #2)

- One way to avoid rep exposure is to exploit the immutability of (other) ADTs the implementation uses
  - aliasing is no problem if nobody can change data
    - have to mutate the rep to break the rep invariant

- Examples (assuming **`Point`** is an *immutable* ADT):

```
class Line {
    private Point s, e;
    public Line(Point s, Point e) {
        this.s = s;
        this.e = e;
    }
    public Point getStart() {
        return this.s;
    }
    …
```

Alternative #3

```
// returns: elts currently in the set
public List<Character> getElts() { // version 1
    return new ArrayList<Character>(elts);//copy out!
}

public List<Character> getElts() { // version 2
    return Collections.unmodifiableList(elts);
}
```

From the JavaDoc for **`Collections.unmodifiableList`**:

Returns an unmodifiable view of the specified list. This method allows modules to provide users with "read-only" access to internal lists. Query operations on the returned list "read through" to the specified list, and attempts to modify the returned list... result in an **`UnsupportedOperationException`**.

The good news

```
public List<Character> getElts() { // version 2
    return Collections.unmodifiableList(elts);
}
```

- Clients cannot *modify (mutate)* the rep
  - cannot break the rep invariant
- (For long lists) more efficient than copy out
- Uses standard libraries

The bad news

```
public List<Character> getElts() { // version 1
     return new ArrayList<Character>(elts); //copy out!
}
```

```
public List<Character> getElts() { // version 2
    return Collections.unmodifiableList(elts);
}
```

The two implementations do not do the same thing!

- both avoid allowing clients to break the rep invariant
- both return a list containing the elements

But consider:

```
xs = s.getElts();
s.insert('a');
xs.contains('a');
```

Version 2 is *observing* an exposed rep, leading to different behavior

Different specifications

Ambiguity of "returns a list containing the current set elements"

"returns a fresh mutable list containing the elements in the set *at the time of the call*"

vs.

"returns read-only access to a list that the ADT *continues to update to hold the current elements in the set*"

A third spec weaker than both [but less simple and useful!]

"returns a list containing the current set elements. *Behavior is unspecified (!) if* client attempts to mutate the list or to access the list after the set's elements are changed"

Also note: Version 2's spec also makes changing the rep later harder

- only "simple" to implement with rep as a **`List`**

Suggestions

Best options for implementing `getElts()`

- if O(n) time is acceptable for relevant use cases, copy the list
  - safest option
  - best option for changeability
- if O(1) time is required, then return an unmodifiable list
  - prevents breaking rep invariant
  - clearly document that behavior is unspecified after mutation
  - ideally, write your own unmodifiable view of the list that throws an exception on all operations after mutation
- if O(1) time is required and there is no unmodifiable version and you don't have time to write one, expose rep and feel very, very guilty

Abstraction Functions

Specifying an ADT

Different types of operations:

1. **`creators`**
2. **`observers`**
3. **`producers`**
4. **`mutators`** (if mutable)

Described in terms of how they change the **abstract state**

- abstract description of what the object means
  - difficult (unless concept is already familiar) but vital
- specs have no information about concrete representation
  - leaves us free to change those in the future

Connecting implementations to specs

For implementers / debuggers / maintainers of the implementation:

Representation Invariant: maps Object → boolean

- we saw this earlier!

Abstraction Function: maps Object → abstract state

- says what the data structure *means* in vocabulary of the ADT
- maps the fields to the abstract state they represent
  - can check that the abstract value after each method meets the postcondition described in the specification

Example: Circle

```
/** Represents a mutable circle in the plane. For example,
  * it can be a circle with center (0,0) and radius 1. */
public class Circle {

  // Rep invariant: center != null and rad > 0
  private Point center;
  private double rad;

  // Abstraction function:
  // AF(this) = a circle with center at this.center
  //   and radius this.rad

  //  ...
}
```

Example: Circle 2

```java
/** Represents a mutable circle in the plane. For example,
  * it can be a circle with center (0,0) and radius 1. */
public class Circle {

  // Rep invariant: center != null and edge != null
  //   and !center.equals(edge)
  private Point center, edge;

  // Abstraction function:
  // AF(this) = a circle with center at this.center
  //   and radius this.center.distanceTo(this.edge)

  //  ...
}
```

Example: Polynomial

```
/** An immutable polynomial with integer coefficients.
  * Examples include 0, 2x, and x + 3x^2 + 5x. */
public class IntPoly {

  // Rep invariant: coeffs != null
  private final int[] coeffs;

  // Abstraction function:
  // AF(this) = sum of this.coeffs[i] * x^i
  //   for i = 0 .. this.coeffs.length

  // ... coeff, degree, etc.
```

Example: Polynomial 2

```
/** An immutable polynomial with integer coefficients.
  * Examples include 0, 2x, and x + 3x^2 + 5x. */
public class IntPoly {

  // Rep invariant: terms != null and
  //     no two terms have the same degree and
  //     terms is sorted in descending order by degree
  private final LinkedList<IntTerm> terms;

  // Abstraction function:
  // AF(this) = sum of monomials in this.terms

  //  ... coeff, degree, etc.
```

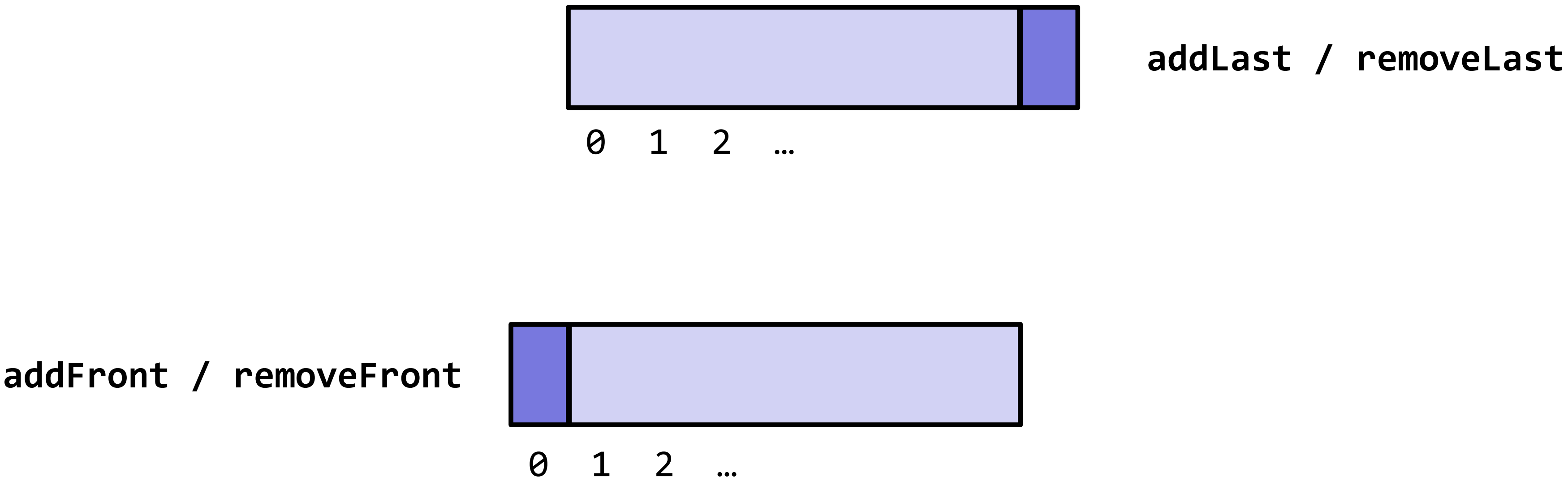
The abstraction function

- Purely conceptual (not a Java function)

- Allows us to check correctness
  - use reasoning to show that the method leaves the abstract state such that it satisfies the postcondition

Example: IntDeque

```
// List that only allows insert/remove at ends.
```



Example: IntDeque

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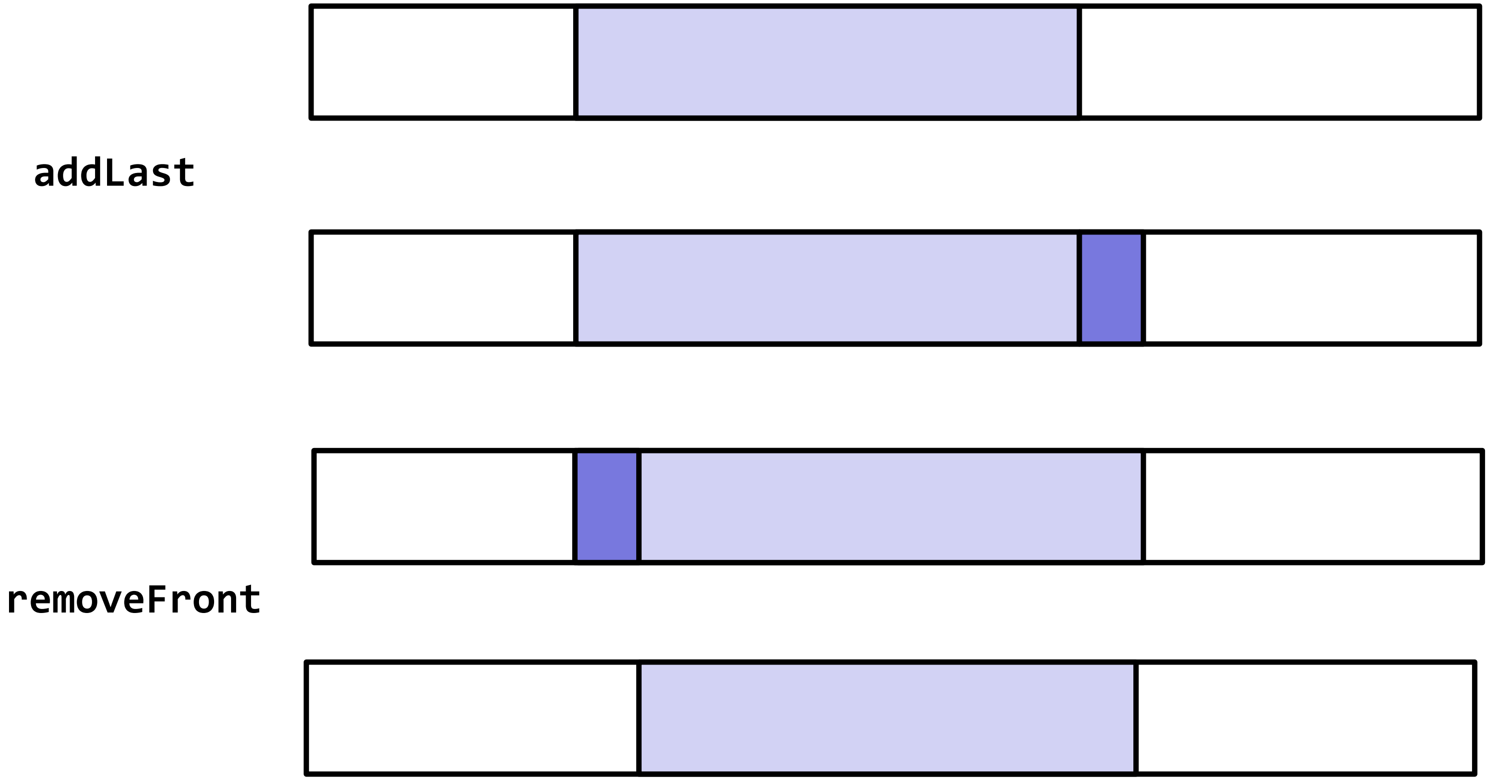


Example: IntDeque

```
// List that only allows insert/remove at ends.
```

`addLast + removeFront`

`addLast + removeFront`

`addLast + removeFront`

Example: IntDeque

```
// List that only allows insert/remove at ends.
```

= (start+len) **mod** vals.length

= `start + len – vals.length`

Example: IntDeque

```
/** List that only allows insert/remove at ends. */
public class IntDeque {

  // AF(this) =
  //   vals[start..start+len-1]      if start+len <= vals.length
  //   vals[start..] + vals[0..?]    otherwise
  private int[] vals;
  private int start, len;

  // Creates an empty list.
  public IntDeque() {
      vals = new int[3];
      start = len = 0;
  }
```

← AF(this) = vals[0..-1] = []

Example: IntDeque

```
/** List that only allows insert/remove at ends. */
public class IntDeque {

  // AF(this) =
  //   vals[start..start+len-1]      if start+len <= vals.length
  //   vals[start..] + vals[0..?]    otherwise
  private int[] vals;
  private int start, len;

  // ...

  // @return length of the list
  public int getLength() {
      return len;
  }
```

Example: IntDeque

```
// List that only allows insert/remove at ends.
```

`#items = len`

`#items = vals.length – (start – k)        (= len?)`

holds iff `k = start + len – vals.length`

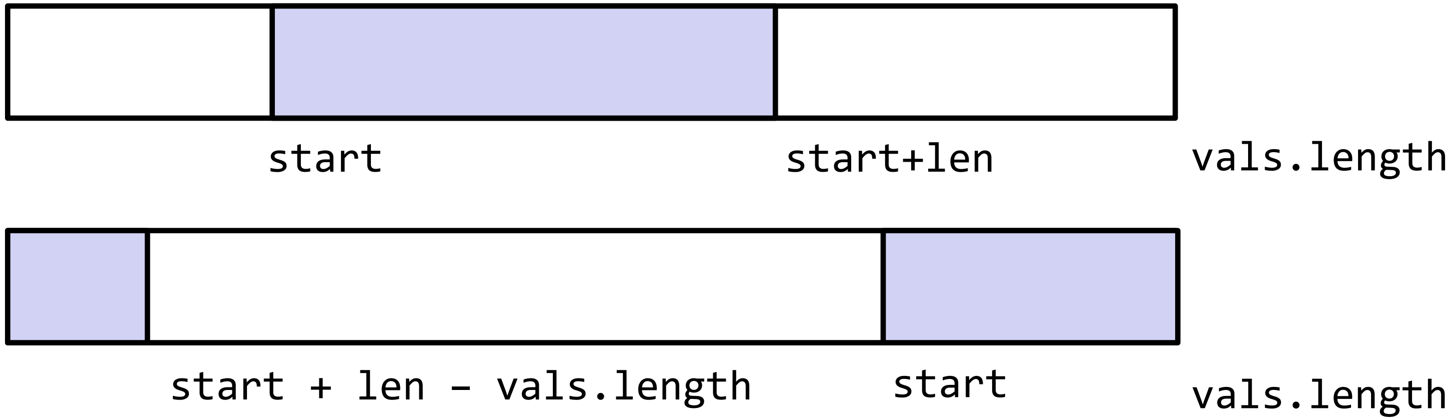
Example: IntDeque

```
/** List that only allows insert/remove at ends. */
public class IntDeque {

  // AF(this) =
  //   vals[start..start+len-1]      if start+len <= vals.length
  //   vals[start..] + vals[0..k]    otherwise
  private int[] vals;
  private int start, len;

  // ...

  // @return length of the list
  public int getLength() {
      return len;
  }
```

1 line of code
but 2 cases for reasoning

Example: IntDeque

```
/** List that only allows insert/remove at ends. */
public class IntDeque {

  // @requires 0 <= i < length
  // @return this[i]
  public int get(int i) { ... }
```



Example: IntDeque

```
/** List that only allows insert/remove at ends. */
public class IntDeque {

  // @requires 0 <= i < length
  // @return this[i]
  public int get(int i) {
      if (start + len <= vals.length) {
          return vals[start + i];
      } else {
          return vals[(start + i) % vals.length];
      }
  }
```

Example: IntDeque

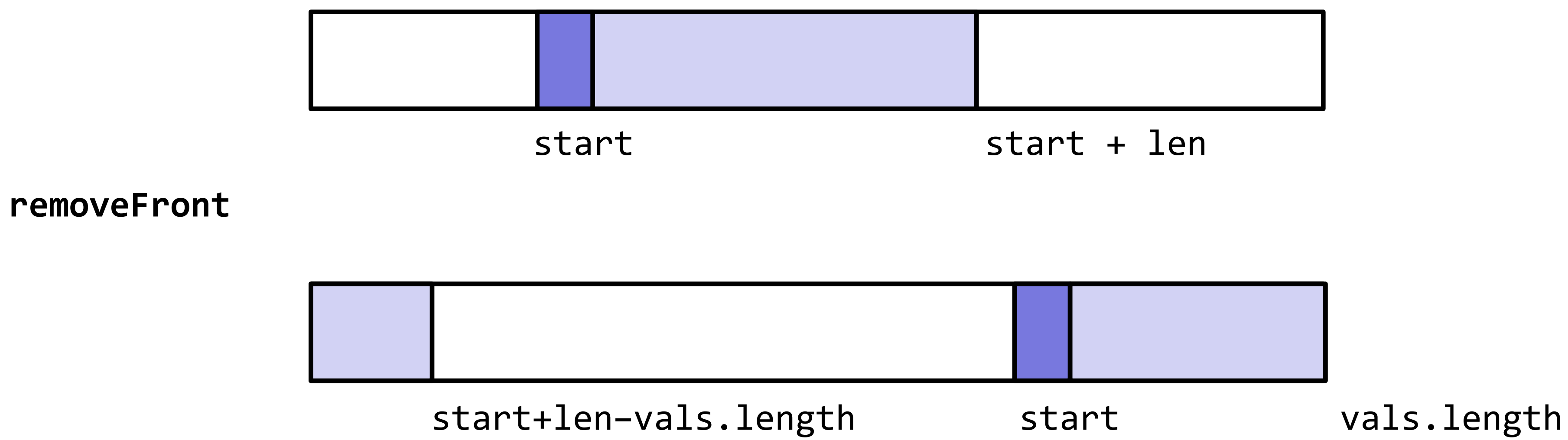
```
/** List that only allows insert/remove at ends. */
public class IntDeque {

  // @requires 0 <= i < length
  // @return this[i]
  public int get(int i) {
      return vals[(start + i) % vals.length];
  }
```

Example: IntDeque

```
/** List that only allows insert/remove at ends. */
public class IntDeque {

  // @requires list length > 0
  // @modifies this
  // @effects first element of list is removed
  // @return value at the front of the list
  public int removeFront() { ... }
```

Example: IntDeque

```
// List that only allows insert/remove at ends.
```



Example: IntDeque

```
// AF(this) =
//   vals[start..start+len-1]      if start+len <= vals.length
//   vals[start..] + vals[0..k]    otherwise

// @requires list length > 0
// @modifies this
// @effects first element of list is removed
public void removeFront() {
    if (start + 1 < vals.length) {
        start += 1;
    } else {
        start = 0;
    }
    len -= 1;
}
```

Example: IntDeque

```
// AF(this) =
//   vals[start..start+len-1]      if start+len <= vals.length
//   vals[start..] + vals[0..k]    otherwise

// @requires list length > 0
// @modifies this
// @effects first element of list is removed
public void removeFront() {
    start = (start + 1) % vals.length;
    len -= 1;
}
```

Example: IntDeque

```
// AF(this) =
//   vals[start..start+len-1]     if start+len <= vals.length
//   vals[start..] + vals[0..k]   otherwise

// @requires list length > 0
// @modifies this
// @effects first element of list is removed
// @return value at the front of the list
public int removeFront() {
    int val = get(0);
    start = (start + 1) % vals.length;
    len -= 1;
    return val;
}
```

Before next class…

1. Start on Prep. Quiz: HW3 as early as possible!
   - Reminds you about common base operations

2. Enjoy the holiday!

Extra: Abstract Interpretation

- Abstraction functions are good for much more (e.g. program analysis)

Extra: Testing

- What is testing? What makes something a good test case?