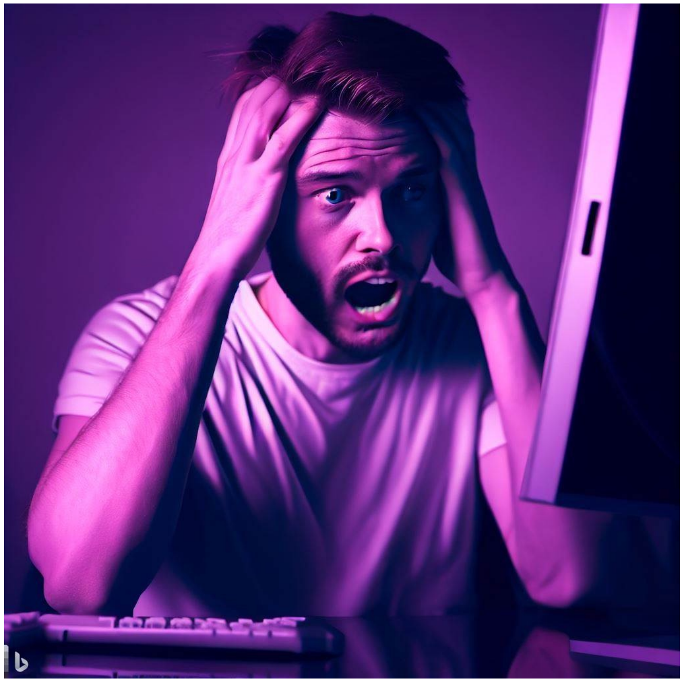


CSE 331

Aliasing

Kevin Zatloukal

Administrivia

- HW6 released
  - starter early
  - last problem may be especially tricky

- Array problems
  - invariants can have a lot of parts
  - lots of places to make mistakes

Level 3

Revisiting HW2

- In HW2, we wrote a function to flip squares
  - solution looked like this

```
function sflip_vert(s: Square): Square {
  switch (s.corner) {
    case NW: return {corner: SW, color: s.color, …};
    case NE: return {corner: SE, color: s.color, …};
    case SW: return {corner: NW, color: s.color, …};
    case SE: return {corner: NE, color: s.color, …};
  }
}
```

  - returns a record that is flipped vertically

Revisiting HW2

- We did not allow mutation in HW2, but now we do
  - many students wanted to write it this way:

```
function sflip(s: Square): Square {
  switch (s.corner) {
    case NW: s.corner = SW; break;
    case NE: s.corner = SE; break;
    case SW: s.corner = NW; break;
    case SE: s.corner = NE; break;
  }
  return s;
}
```

Is this version now correct?

Impossible to say!

Depends who else has a reference to s

Revisiting HW4

- In HW4, color information in a `ColorInfo` record
  - we used a triple, but a record also works

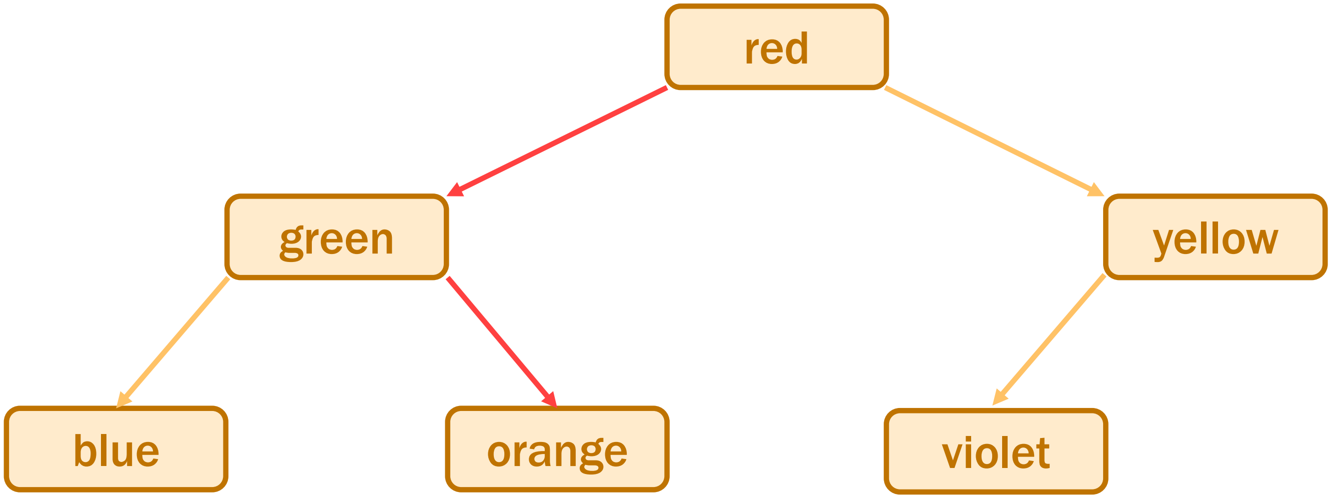
```
type ColorInfo = {
    name: string, cssColor: string, dark: boolean};
```

- Could also write functions that mutate them:

```
function makeFavColor(c: ColorInfo): ColorInfo {
  c.name = “pink”;
  c.cssColor = “#FFC0CB”;
  c.dark = false;
  return c;
}
```

Revisiting HW4

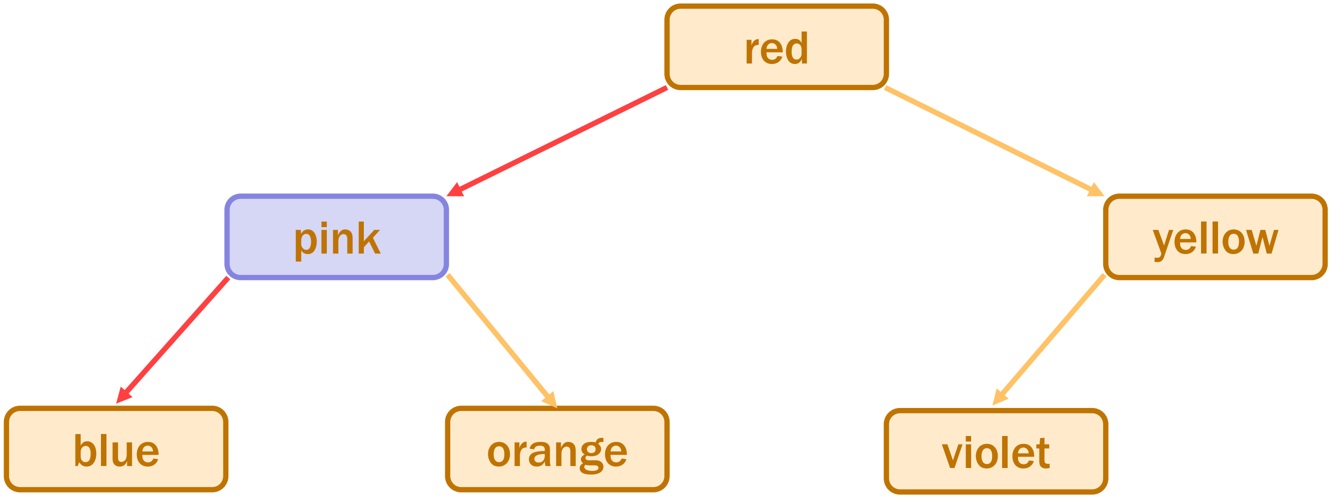
- In HW4, we had a BST of `ColorInfo` records
  - faster way to look up color information
  - e.g., find <u>**orange**</u> like this



- Suppose we called `makeFavColor` on the green record…

Revisiting HW4

- **Suppose we called `makeFavColor` on green record...**
  - **it is mutated into pink**
  - **now this happens when we look for <u>orange</u>:**



  - **it can no longer be found!**

    we violated the BST invariant

Revisiting HW2

- In HW2, we wrote a function to flip squares
  - solution looked like this

```
function sflip_vert(s: Square): Square {
  switch (s.corner) {
    case NW: return {corner: SW, color: s.color, …};
    case NE: return {corner: SE, color: s.color, …};
    case SW: return {corner: NW, color: s.color, …};
    case SE: return {corner: NE, color: s.color, …};
```

Scary Bugs

- Do not fear crashes
  - those are easy to spot and fix

    get a stack trace that tells you exactly where it went wrong

- Do fear unexpected mutation
  - failure will give you no clue what went wrong

    will take a long time to realize the BST invariant was violated by mutation

  - bug could be almost anywhere in the code

    anyone who mutates a `ColorInfo` could have caused it

  - could take *weeks* to track it down

Level 3: Mutable Heap State

- “With great power, comes great responsibility”

- With arrays:
  - gain the ability to easily access any element
  - must keep track of information about the whole array

- Multiple references to the same object are “aliases”

- With mutable heap state:
  - gain efficiency in some cases
  - must keep track of every alias that could mutate that state

    any alias, anywhere in the *entire* program could cause a bug

Easy Ways to Stay Safe

1. Do not use mutable state
   - don’t need to think about aliasing at all
   - any number of aliases is fine

2. Do not allow aliases
   - never give anyone else an alias
   - create the state in your constructor:

```
class MyClass {
  vals: string[];

  constructor() {
    this.vals = new Array(0);  // only alias
  }
  …
```

Easy Ways to Stay Safe

1. Do not use mutable state
   - don’t need to think about aliasing at all
   - any number of aliases is fine

2. Do not allow aliases
   - never give anyone else an alias
   - create the state in your constructor

3. Make a copy of anything you want to keep
   - you have the only reference to the newly created copy
   - does not matter if the caller later mutates the original

An Advanced (Two-Stage) Approach

- Mutable object has only one usable alias (owner)
  - one reference that is allowed to use & mutate it

- Must track ownership of each mutable object
  - can be passed in a function call
  - passed permanently or just “borrowed”

    borrowing returns ownership back when the call ends

- Object can be “frozen”, making it immutable
  - no longer necessary to track ownership

- Rust language has built-in support for this
  - better tool support

Mutable ADTs

ADTs

- Main place we have heap state is in an ADT
- Previously:
  - state was immutable
  - set in the constructor and then never changed

    only need to confirm RI holds at the end of the constructor

    if RI holds there, then it holds forever
- Now:
  - allow state to be changed by methods

ADTs

- Main place we have heap state is in an ADT
- Now:
  - allow state to be changed by methods
- Taxes:
  - more complex specifications

    add `@effects` and `@modifies`
  - must check the RI holds after any method that mutates

    often a good idea to write code to check this at runtime
  - must avoid aliasing of anything mutable

    we call this "representation exposure"

Recall: List ADT with a Fast `getLast`

```
// Represents an (immutable) list of numbers.
interface FastList {

  // @returns cons(x, obj)
  cons(x: number): FastList;

  // @returns last(obj)
  getLast(): number|undefined;

  // @returns obj
  toList(): List<number>;
};

function makeFastList(): FastList {
  return new FastListImpl(nil);
}
```

producer method

Mutable List ADT with a Fast `getLast`

```
// Represents a mutable list of numbers.
interface MutableFastList {

  // @modifies obj
  // @effects obj = cons(x, obj_0)
  cons(x: number): void;

  …
```

mutator method

- Method `cons` changes the list, putting `x` in front
  - now returns `void`
  - mutation explained in `@modifies` and `@effects`

    abstract state is the old abstract state with x put in front

Mutable List ADT with a Fast `getLast`

```
// Represents a mutable list of numbers.
interface MutableFastList {

  // @modifies obj
  // @effects obj = cons(x, obj_0)
  cons(x: number): void;

  …
```

mutator method

- Method `cons` changes the list, putting `x` in front
  - mutable data type

    clients need to worry about aliasing
  - don't make a tree of these!

    some languages (e.g., Python) don't allow this

Recall: One Concrete Rep for `FastList`

```
class FastListImpl implements FastList {

  // RI: this.last = last(this.list)
  // AF: obj = this.list
  readonly last: number | undefined;
  readonly list: List<number>;

  constructor(list: List<number>) {
    this.list = list;
    this.last = last(this.list);
  }
```

- We can use the same rep for a mutable version

Mutable List ADT with a Fast `getLast`

```
class MutableFastListImpl implements MutableFastList {

  // RI: this.last = last(this.list)
  // AF: obj = this.list
  readonly last: number | undefined;
  readonly list: List<number>;

  // @modifies obj
  // @effects obj = cons(x, obj_0)
  cons = (x: List<number>): void => {
    this.list = cons(x, this.list);
  };
```

- Let’s check correctness…

Mutable List ADT with a Fast `getLast`

```
class MutableFastListImpl implements MutableFastList {
  // RI: this.last = last(this.list)
  // AF: obj = this.list
  readonly last: number | undefined;
  readonly list: List<number>;

  // @modifies obj
  // @effects obj = cons(x, obj_0)
  cons = (x: List<number>): void => {
    this.list = cons(x, this.list);
    {{ this.list = cons(x, this.list_0) }}
    {{ Post: obj = cons(x, obj_0) }}
  };
```

Mutable List ADT with a Fast `getLast`

```
class MutableFastListImpl implements MutableFastList {
  // RI: this.last = last(this.list)
  // AF: obj = this.list
  readonly last: number | undefined;
  readonly list: List<number>;

  // @modifies obj
  // @effects obj = cons(x, obj_0)
  cons = (x: List<number>): void => {
    this.list = cons(x, this.list);
```

{{ $\text{this.list} = \text{cons}(x, \text{this.list}_0)$ }}

{{ **Post**: $\text{obj} = \text{cons}(x, \text{obj}_0)$ }}

```
  };
```

What is missing?

Also, need the RI to hold!

$\text{obj} = \text{this.list}$	by AF
$= \text{cons}(x, \text{this.list}_0)$	since $\text{this.list} = \text{cons}(x, \text{this.list}_0)$
$= \text{cons}(x, \text{obj}_0)$	by AF

Mutable List ADT with a Fast `getLast`

```
class MutableFastListImpl implements MutableFastList {
  // RI: this.last = last(this.list)
  // AF: obj = this.list
  readonly last: number | undefined;
  readonly list: List<number>;

  // @modifies obj
  // @effects obj = cons(x, obj_0)
  cons = (x: List<number>): void => {
    this.list = cons(x, this.list);
```

{{ this.list = cons(x, this.list$_0$) }}

{{ **Post**: obj = cons(x, obj$_0$) and
this.last = last(this.list) }}

```
  };
```

Also, need the RI to hold!

Does it? No!

- Postcondition is `@returns`, `@effects`, and <u>RI</u>

Mutable List ADT with a Fast `getLast`

```
class MutableFastListImpl implements MutableFastList {
  // RI: this.last = last(this.list)
  // AF: obj = this.list
  readonly last: number | undefined;
  readonly list: List<number>;

  // @modifies obj
  // @effects obj = cons(x, obj_0)
  cons = (x: List<number>): void => {
    this.list = cons(x, this.list);
    this.last = last(this.list);
    {{ this.list = cons(x, this.list_0) and this.last = last(this.list) }}
    {{ Post: obj = cons(x, obj_0) and this.last = last(this.list) }}
  };
```

Rep Invariant now holds

Mutable List ADT with a Fast `getLast`

```
class MutableFastListImpl implements MutableFastList {
  // RI: this.last = last(this.list)
  // AF: obj = this.list
  readonly last: number | undefined;
  readonly list: List<number>;

  // @modifies obj
  // @effects obj = cons(x, obj_0)
  cons = (x: List<number>): void => {
    this.last = last(this.list);
    {{ this.last = last(this.list) }}
    this.list = cons(x, this.list);
    {{ this.list = cons(x, this.list_0) and this.last = last(this.list_0) }}
    {{ Post: obj = cons(x, obj_0) and this.last = last(this.list) }}
  };
```

Rep Invariant would not hold if we switched the order

Mutable List ADT with a Fast `getLast`

```
class MutableFastListImpl implements MutableFastList {
  // RI: this.last = last(this.list)
  // AF: obj = this.list
  readonly last: number | undefined;
  readonly list: List<number>;

  // @modifies obj
  // @effects obj = cons(x, obj_0)
  cons = (x: List<number>): void => {
    this.list = cons(x, this.list);
    this.last = last(this.list);
```

{{ this.list = cons(x, this.list_0) and this.last = last(this.list) }}

{{ **Post**: obj = cons(x, obj_0) and this.last = last(this.list) }}

```
  };
```

This version is obviously correct, but O(n).

Can we do it faster?

Mutable List ADT with a Fast `getLast`

```
class MutableFastListImpl implements MutableFastList {
  // RI: this.last = last(this.list)
  // AF: obj = this.list
  readonly last: number | undefined;
  readonly list: List<number>;

  // @modifies obj
  // @effects obj = cons(x, obj_0)
  cons = (x: List<number>): void => {
    if (this.list === nil)
      this.last = x;
    this.list = cons(x, this.list);
```

{{ this.list = cons(x, this.list$_0$) and

(this.list$_0$ = nil and this.last = x or this.list$_0$ $\neq$ nil and this.last = this.last$_0$) }}

{{ **Post**: obj = cons(x, obj$_0$) and this.last = last(this.list) }}

```
};
```

O(1) version, but more complex reasoning ("or"!)

Mutable List ADT with a Fast `getLast`

```
class MutableFastListImpl implements MutableFastList {

  cons = (x: List<number>): void => {
    if (this.list === nil)
      this.last = x;
    this.list = cons(x, this.list);
```

{{ this.list $=$ cons(x, this.list$_0$) and
  (this.list$_0$ $=$ nil and this.last $=$ x or this.list$_0$ $\neq$ nil and this.last $=$ this.last$_0$) }}

{{ **Post**: obj $=$ cons(x, obj$_0$) and this.last $=$ last(this.list) }}

```
  };
```

Case this.list$_0$ $=$ nil:

this.last	$=$ x	
	$=$ last(cons(x, nil))	**def of** last
	$=$ last(cons(x, this.list$_0$))	**since** this.list$_0$ $=$ nil
	$=$ last(this.list)	**since** this.list $=$ cons(x, …)

Mutable List ADT with a Fast `getLast`

```
class MutableFastListImpl implements MutableFastList {

  cons = (x: List<number>): void => {
    if (this.list === nil)
      this.last = x;
    this.list = cons(x, this.list);
    {{ this.list = cons(x, this.list_0) and
      (this.list_0 = nil and this.last = x or this.list_0 ≠ nil and this.last = this.last_0) }}
    {{ Post: obj = cons(x, obj_0) and this.last = last(this.list) }}
  };
```

Case $\text{this.list}_0 \neq \text{nil}$:

$$\begin{aligned} \text{this.last} &= \text{this.last}_0 && \\ &= \text{last}(\text{this.list}_0) && \textbf{by RI} \\ &= \text{last}(\text{cons}(x, \text{this.list}_0)) && \textbf{since } \text{this.list}_0 \neq \text{nil} \\ &= \text{last}(\text{this.list}) && \textbf{since } \text{this.list} = \text{cons}(x, \ldots) \end{aligned}$$

Moral of the Story for Level 3

- More mutation gave us better efficiency
  - saved memory
  - immutable version could be just as fast (level 1)

- More mutation means more complex reasoning
  - more facts to keep track of
  - more ways to make mistakes
  - more work to make sure we did it right

Recall: Immutable Queue ADT

- A queue is a list that can *only* be changed two ways:
  - add elements to the front
  - remove elements from the back

```
// List that only supports adding to the front and
// removing from the end
interface NumberQueue {
```

observer

```
  // @returns len(obj)
  size(): number;
```

producer

```
  // @returns cons(x, obj)
  enqueue(x: number): NumberQueue;
```

producer

```
  // @requires len(obj) > 0
  // @returns (x, Q) with obj = concat(Q, cons(x, nil))
  dequeue(): [number, NumberQueue];
}
```

Mutable Queue ADT

- Mutable versions has mutators instead of producers

```
// Mutable array that only supports adding to the front
// and removing from the end.
interface MutableNumberQueue {
```

observer

```
  // @returns obj
  elements(): number[];
```

mutator

```
  // @modifies obj
  // @effects obj = [x] ++ obj_0
  enqueue(x: number): void;
```

mutator

```
  // @requires len(obj) > 0
  // @modifies obj
  // @effects obj_0 = obj ++ [x]
  // @returns x
  dequeue(): number;
}
```

Recall: Implementing a Queue with Two Lists

```
// Implements a queue using two lists.
class ListPairQueue implements NumberQueue {

  // AF: obj = concat(this.front, rev(this.back))
  // RI: if this.back = nil, then this.front = nil
  readonly front: List;
  readonly back: List;

  // makes obj = concat(front, rev(back))
  constructor(front: List, back: List) {
    …
  }
```

- Queue was in two parts, front and back
  - back stored in reverse order
  - full list was concat(this.front, rev(this.back)

Implementing Mutable Queue with Two Arrays

```
// Implements a mutable queue using two arrays.
class ArrayPairQueue implements MutableNumberQueue {

  // AF: obj = rev(this.front) ++ this.back
  readonly front: number[];
  readonly back: number[];

  // makes obj = vals
  constructor(vals: number[]) {
    this.front = [];
    this.back = vals;
  }
```

We should check this…

Implementing Mutable Queue with Two Arrays

```
// Implements a mutable queue using two arrays.
class ArrayPairQueue implements MutableNumberQueue {

  // AF: obj = rev(this.front) ++ this.back
  readonly front: number[];
  readonly back: number[];

  // makes obj = vals
  constructor(vals: number[]) {
    this.front = [];
    this.back = vals;
    {{ this.front = [] and this.back = vals }}
    {{ Post: obj = vals }}
  }
```

Implementing Mutable Queue with Two Arrays

```
// Implements a mutable queue using two arrays.
class ArrayPairQueue implements MutableNumberQueue {

  // AF: obj = rev(this.front) ++ this.back
  readonly front: number[];
  readonly back: number[];

  // makes obj = vals
  constructor(vals: number[]) {
    this.front = [];
    this.back = vals;
    {{ this.front = [] and this.back = vals }}
    {{ Post: obj = vals }}
  }
```

Is this really correct?

No way to say!

obj	= rev(this.front) ⧺ this.back	**by AF**
	= rev([]) ⧺ this.back	**since** this.front = []
	= [] ⧺ this.back	**def of** rev
	= this.back = vals	**since** this.back = vals

Implementing Mutable Queue with Two Arrays

```
// Implements a mutable queue using two arrays.
class ArrayPairQueue implements MutableNumberQueue {

  // AF: obj = rev(this.front) ++ this.back
  readonly front: number[];
  readonly back: number[];

  // makes obj = vals
  constructor(vals: number[]) {
    this.front = [];
    this.back = vals.slice(0, vals.length);
  }
```

- Make a copy of the array
  - we have the only reference to it (no aliases)

Implementing Mutable Queue with Two Arrays

```
// Implements a mutable queue using two arrays.
class ArrayPairQueue implements MutableNumberQueue {

  // AF: obj = rev(this.front) ++ this.back
  readonly front: number[];
  readonly back: number[];

  // @returns obj
  elements(): number[] {
    let revFront: number[] =
      this.front.slice(0, this.front.length);
    revFront.reverse();
    return revFront.concat(this.back);
  };
```

This is slow…

We can optimize it if front = [].

$$\text{rev}([\,]) \mathbin{+\!\!+} \text{this.back} = [\,] \mathbin{+\!\!+} \text{this.back} = \text{this.back}$$

Implementing Mutable Queue with Two Arrays

```
// Implements a mutable queue using two arrays.
class ArrayPairQueue implements MutableNumberQueue {

  // AF: obj = rev(this.front) ++ this.back
  readonly front: number[];
  readonly back: number[];

  // @returns obj
  elements(): number[] {
    if (this.front.length === 0) {
      return this.back;   // O(1) when this.front = []
    } else {
      let revFront: number[] =
        this.front.slice(0, this.front.length);
      revFront.reverse();
      return revFront.concat(this.back);
    }
  };
```

Is this correct?

No way to say!

Implementing Mutable Queue with Two Arrays

```
// Implements a mutable queue using two arrays.
class ArrayPairQueue implements MutableNumberQueue {

  // AF: obj = rev(this.front) ++ this.back
  readonly front: number[];
  readonly back: number[];

  // @returns obj
  elements(): number[] {
    let revFront: number[] = this.front.slice(0);
    revFront.reverse();
    return revFront.concat(this.back);
  };
```

- Cannot return an alias to `this.back`
  - must make a copy in all cases

Avoiding Representation Exposure

- **Prevent aliasing of mutable state**
  - **otherwise, code outside your class can break it**

- **Options for avoiding representation exposure:**

  1. **Copy In, Copy Out**

     store copies of mutable values passed to you

     return copies of not aliases to mutable state

     don't take their word that they haven't kept an alias

  2. **Use immutable types**

     lists are immutable, so you can freely accept and return them

- **Professionals are untrusting about aliases**