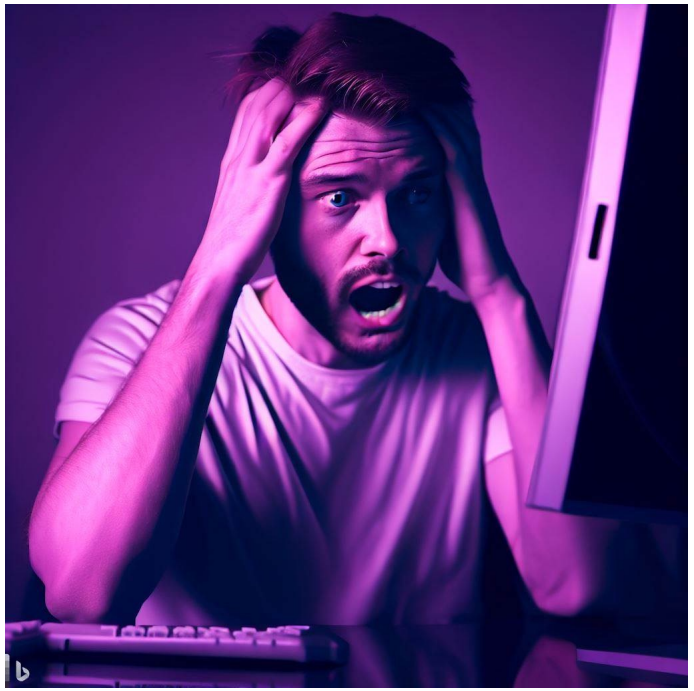


CSE 331

Mutable Heap State

Katherine Murphy

Credits: Profs. Kevin Zatloukal and James Wilcox

Correctness Levels

Level	Description	Testing	Tools	Reasoning
0	small # of inputs	exhaustive		
1	straight from spec	heuristics	type checking	code reviews
2	no mutation	"	libraries	calculation induction
3	local variable mutation	"	"	Floyd logic
4	array mutation	"	"	for-any facts
5	heap state mutation	"	"	alias tracking rep invariants

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
- Additional 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

Heap State

- "Heap state" = lives on after the call stack finishes
  - after current function and those calling it all return
  - state could be arrays or records
- No different from before when immutable
  - we don't care when the garbage collectors gets rid of it
- Vastly more complex when **mutable**…

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 an object could have caused it
  - could take *weeks* to track it down

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
   a) do not hand out aliases yourself
   b) make a copy of anything you want to keep

ensures only one reference to the object (no aliases)

- For 331, allowing aliases is a bug! ("rep exposure")
  - gives the client the ability to break your code
  - we will stick to these simple strategies for avoiding it

An Advanced (Two-Stage) Approach

- **Mutable object has only one reference (owner)**
  - **one reference that is allowed to use & mutate it**
- **Object is eventually "frozen", making it immutable**
  - **no longer necessary to track ownership**
- **Example: Java's `StringBuilder` vs `String`**
  - `StringBuilder` **is mutable (be careful!)**
  - `StringBuilder.toString` **returns the value as a** `String`
  - `String` **is immutable**

Language Features & Aliasing

- Most recent languages have some answer to this…
- Java chose to make `String` immutable
  - most keys in maps are strings
  - hugely controversial at the time, but great decision
- Python chose to only allow immutable keys in maps
  - only numbers, strings, and tuples allowed
  - surprisingly, not that inconvenient
- Rust has built-in support for tracking ownership
  - ownership can be “borrowed” and returned
  - type system ensures there is only one usable alias

Avoiding Representation Exposure

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

- **Options for avoiding representation exposure:**

  1. **Use immutable types**

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

  2. **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

- **Professionals are untrusting about aliases**

Need for Mutable Heap State

- Saw that mutable heap state is complex
  - better to avoid when possible
- Cannot be avoided in some cases
  1. server-side data storage (HW Chatbot - Final)
  2. client-side UI (HW Squares - Final)
- In both cases, we try to constrain its use
  - including coding conventions to keep ourselves sane

Stateful UI in React (React Components)

UI in HW Fib - Weave

- **UI so far was static**
  - `index.tsx` **calls** `render` **to show a fixed UI**

    UI was different based on query params

    but never changed once rendered

- **Made the UI change by reloading the page**
  - **change the query params, so it renders something different**

UI in HW Fib - Weave

- **Made the UI change by reloading the page**
  - **change the query params, so it renders something different**

http://localhost:8080/

Word: wooow
Algorithm: Crazy Caps
encode decode
Submit

http://localhost:8080/?word=wooow&...

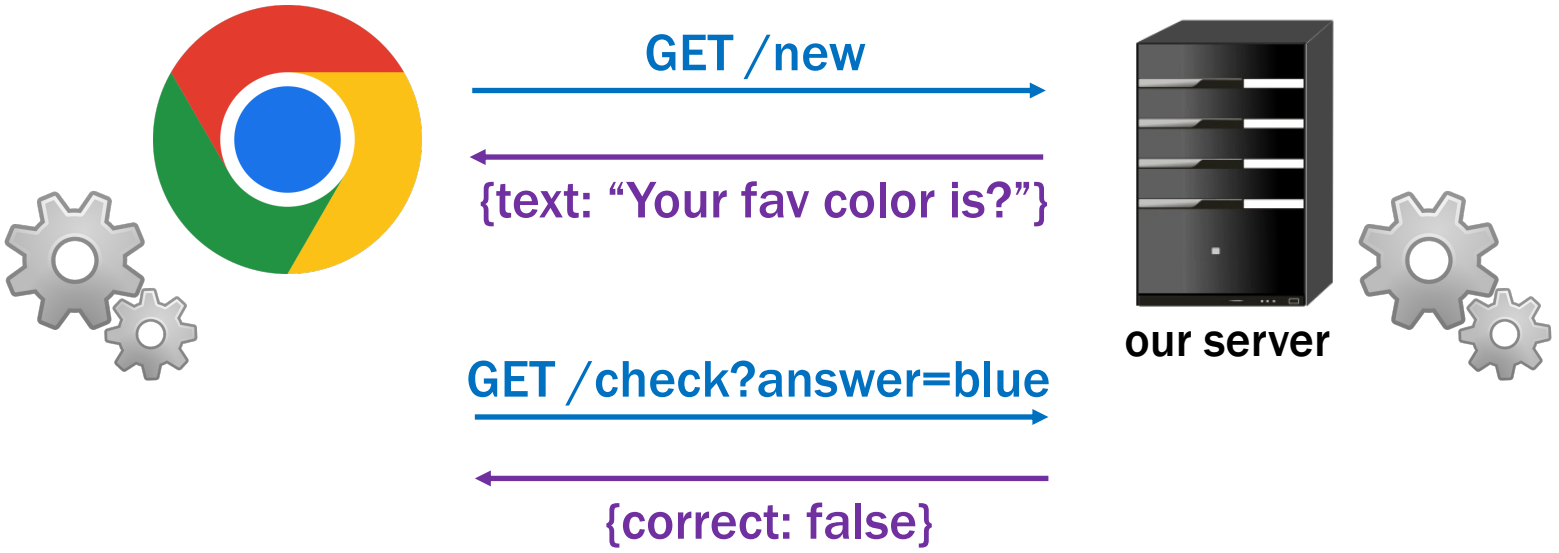
WoOoW

```
const word = params.get("word");
if (word === null) {
  root.render(<MakeForm/>);
} else {
  root.render(<ShowResults word={word} ../>);
}
```

Client-Side State

- **Client needs to update the UI after getting response**
  - **don't want to reload the whole page to redraw**

    reloading is slow and can lose user data (e.g., contents of text fields)
  - **need a way to update the UI without a reload**



React Functions

- **React let us create custom tags**
  - **e.g., from HW Quilt**

```
root.render(<QuiltElem quilt={q}/>);
```

  - **acts like the call**

```
root.render(QuiltElem({quilt: q}));
```

  - **where `QuiltElem` is function taking a record argument**

```
const QuiltElem = (props: {quilt: Quilt}): JSX.Element => {..};
```

- **Render spots `<QuiltElem>` and calls `QuiltElem`**
  - **replaces `<QuiltElem>` with HTML returned by `QuiltElem`**

React Functions

- React let us create custom tags
  - e.g., from HW Quilt

```
root.render(<QuiltElem quilt={q}/>);
```

  - acts like the call

```
root.render(QuiltElem({quilt: q}));
```

  - where `QuiltElem` is function taking a record argument

```
const QuiltElem = (props: {quilt: Quilt}): JSX.Element => {..};
```

- Gives modularity but UI cannot change
  - need *mutable* state to allow the UI to update after events

React Components

- **React also let us create custom tags with classes**
  - **e.g., from HW Quilt**

```
root.render(<QuiltElem quilt={q}/>);
```

  - **acts like the call**

```
root.render(new QuiltElem({quilt: q}).render());
```

  - **where `QuiltElem` is class that takes a record in constructor**

```
class QuiltElem extends Component<{quilt: Quilt}, {}> {
  constructor(props: {quilt: Quilt}) { … /* store props */ }
  render = (): JSX.Element => { … /* return HTML */ };
};
```

Simplest React Component

- **Component that prints a Hello message:**

```
type HelloProps = {name: string};

class Hello extends Component<HelloProps, {}> {
  constructor(props: HelloProps) {
    super(props);
  }
  render = (): JSX.Element => {
    return <p>Hi, {this.props.name}</p>;
  };
}
```

- **Used as** `<Hello name={"Fred"}/>`**:**

Simplest React Component

- Component that prints a Hello message:

```
type HelloProps = {name: string};

class Hello extends Component<HelloProps, {}> {
  constructor(props: HelloProps) {
    super(props);
  }
  render = (): JSX.Element => {
    return <p>Hi, {this.props.name}</p>;
  };
}
```

No sensible reason to make Components without state

- Component is a generic type
  - first type parameter is the type of "`props`"
  - second type parameter is for "`state`"...

Simplest Stateful React Component

```
type HelloProps = {name: string};
type HelloState = {greeting: string};

class Hello extends Component<HelloProps,HelloState>
{
  constructor(props: HelloProps) {
    super(props);
    this.state = {greeting: "Hi"};
  }
```

- Component is a generic type
  - first component is type of `this.props` (readonly)
  - second component is type of `this.state`
- Initialize `this.state` in the constructor
  - never directly modified after that

React Components

```
type HelloProps = {name: string};
type HelloState = {greeting: string};

class Hello extends Component<HelloProps,HelloState>
{

  render = (): JSX.Element {
    return <p>{this.state.greeting},
              {this.props.name}!</p>;
  };
```

- `render` **can use both** `this.props` **and** `this.state`
  - **difference 1: caller give us props, but we set our state**
  - **difference 2: we can *change* our state**
  - **React will automatically re-render when state changes**

    re-render happens shortly after the state change

React Components

```
type HelloProps = {name: string};
type HelloState = {greeting: string};

class Hello extends Component<HelloProps,HelloState>
{
  …
  setGreeting = (newGreeting: string): void => {
    this.setState({greeting: newGreeting});
  };
}
```

- **Must call `setState` to change the state**
  - **directly modifying `this.state` is a (painful) bug**

    our linter will prevent this, thankfully

- **React will automatically re-render when state changes**
  - **this is the (only) reason to use a Component**

React Components

```
type HelloProps = {name: string};
type HelloState = {greeting: string};

class Hello extends Component<HelloProps,HelloState>
{
  …
  setGreeting = (newGreeting: string): void => {
    this.setState({greeting: newGreeting});
  };
}
```

- **Must call `setState` to change the state**
  - **directly modifying `this.state` is a (painful) bug**

    our linter will prevent this, thankfully

- **Only need to supply the fields that have changed**
  - **all the other fields will stay as they were before**

React Components

```
type HelloProps = {name: string};
type HelloState = {greeting: string};

class Hello extends Component<HelloProps,HelloState>
{
  constructor(props: HelloProps) {
    super(props);
    this.state = {greeting: "Hi"};
  }

  render = (): JSX.Element {
    return <p>{this.state.greeting},
              {this.props.name}!</p>;
  };

  setGreeting = (newGreeting: string): void => {
    this.setState({greeting: newGreeting});
  };
}
```

React Components

```
type HelloProps = {name: string};
type HelloState = {greeting: string};

class Hello extends Component<HelloProps,HelloState>
{
  …
  setGreeting = (newGreeting : string): void => {
    this.setState({greeting: newGreeting});
  };
}
```

- **How could `setGreeting` be called?**
  - **typically happens in a handler for an HTML event**

React Component with an Event Handler

- **Pass method to be called as argument (a "callback")**
  - **value of `onClick` attribute is our `makeSpanish` method**

```
render = (): JSX.Element {
   return (<div>
       <p>{this.state.greeting}, {this.props.name}!</p>
       <button onClick={this.doEspClick}>Espanol</button>
     </div>);
 };
```

- **Browser will invoke that method when button is clicked**

```
doEspClick = (evt: MouseEvent<HTMLButtonElement>) => {
   this.setState({greeting: "Hola"});
 };
```

  - **Call to `setState` causes a re-render (in a bit)**

React Component with an Event Handler

```
type HelloProps = {name: string};
type HelloState = {greeting: string};

class Hello extends Component<HelloProps, HelloState> {
  constructor(props: HelloProps) {
    super(props);
    this.state = {greeting: "Hi"};
  }

  render = (): JSX.Element {
    return (<div>
        <p>{this.state.greeting}, {this.props.name}!</p>
        <button onClick={this.doEspClick}>Espanol</button>
      </div>);
  };

  doEspClick = (evt: MouseEvent<HTMLButtonElement>) => {
    this.setState({greeting: "Hola"});
  };
```

React Component with an Event Handler

- **Pass method to be called as argument (a "callback")**
  - **value of `onClick` attribute is our `makeSpanish` method**

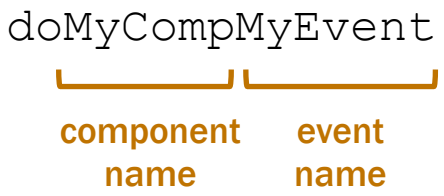
```
render = (): JSX.Element {
   return (<div>
       <p>{this.state.greeting}, {this.props.name}!</p>
       <button onClick={this.doEspClick()}>Espanol</button>
     </div>);
 };
```

- **Including parentheses here is a (painful) bug!**
  - **that would call the method inside render**

    passing its return value as the value of the `onClick` attribute
  - **we want to pass the method to the button, and have it called when the click occurs**

Event Handler Conventions

- We will use this convention for event handlers



  - e.g., `doAddClick`, `doNewNameChange`

- Reduces the need to explain these methods
  - method name is enough to understand what it is for
  - method name is the only thing you know they read

- Components should be just rendering & event handlers

React Components are Like Java Classes

```
type HelloProps = {name: string};
type HelloState = {greeting: string};
```

- "Props" are part of the specification (arguments)
  - public interface, used by clients

```
root.render(<Hello name={"Fred"}/>);  // pass in
name
```

- "State" is like the concrete representation
  - private choice of data structures, hidden from clients

```
constructor(props: HelloProps) {
  super(props);
  this.state = {greeting: "Hi"};    // initial state
}
```

React Components are Like Java Classes

HTML on screen = render(this.state)

	Component	React
t = 10	this.state = s_1	doc = $HTML_1$ = render(s_1)
t = 20	this.setState(s_2)	
t = 30		this.state = s_2 doc = $HTML_2$ = render(s_2)

React updates this.state **to** s_2 **and** doc **to** $HTML_2$ ***simultaneously***

React Components are Like Java Classes

HTML on screen = render(this.state)

- **Don't want to be in a state where that is not true**

  ...unless you enjoy painful debugging

1. **Do not mutate `this.state` (call `setState`)**

   React will update `this.state` and HTML on screen at the same time

   Easy way to ensure this: disallow mutation in the client

   We'll use that rule this quarter.

React Components are Like Java Classes

$$\text{HTML on screen} = \text{render}(\text{this.state})$$

- **Don't want to be in a state where that is not true**

  ...unless you enjoy painful debugging

1. **Do not mutate `this.state` (call `setState`)**

   React will update `this.state` and HTML on screen at the same time

2. **Make sure no data on screen would disappear on re-render**

   More on this later…

React Components have Mutable Heap State

- Like Java Classes, methods are sharing state
  - change in one method is read in other methods
- Error in one method (writing) fails in another (reading)
  - debugging will be harder!
- HW Squares - Final are the debugging assignments
  - necessary to understand all the parts of the code

React Components have Mutable Heap State

- **Hard debugging makes correctness more important**

- **Move complex parts into separate functions**
  - **test and reason carefully through those functions**
  - **class is ideally just be rendering and event handlers**

    move everything complex into helper functions

    e.g., calculation of new state can be a helper function
  - **harder to reason about and test with mutable heap state, so keep it simple**

- **Write code to check your invariants**
  - **ensure the new state is valid before calling `setState`**
  - **practice defensive programming**

Example: To-Do List (v1)

TodoApp – State

```
// Represents one item in the todo list.
type TodoItem = {
  name: string;
  completed: boolean;
};

// Client gives us the initial (complete) list of items.
type TodoProps = {
  initialItems: TodoItem[];  // items to show initially
};

// State of the app is the current list of items,
// which will be the initial list with some possibly removed.
type TodoState = {
  items: TodoItem[];         // current list of items
};
```

TodoApp – Class

```
// Application that displays a to-do list.
export class Todo extends Component<TodoProps, TodoState> {

  constructor(props: TodoProps) {
    super(props);

    this.state = {items: props.initialItems.slice(0)};
  }

  …
```

TodoApp – Render

```
// Return a UI with all the items and elements that allow them to
// add a new item with a name of their choice.
render = (): JSX.Element => {
  return (
    <div>
      <h2>To-Do List</h2>
      {this.renderItems()}
    </div>);
};
```

TodoApp – Render Items (abbreviated)

```
renderItems = (): JSX.Element[] => {
  const items: JSX.Element[] = [];
  for (const item of this.state.items) {
    const i = this.state.items.findIndex((i) => i === item);
    const id = = "check_" + i;
    if (items.completed) {
      items.push(
        <div key={i}>
          <input type="checkbox" id={id} checked ={true}
           readOnly={true}/>
          <label className="completed" htmlFor={id}>
           {item.name}
          </label>
        </div>);
    } else { … /* read-only once completed */ }
  }
  return items;
};
```

TodoApp – Item Click

```
// Called when the user clicks on an item.
// Removes it from the list and redraws
doItemClick = (_: ChangeEvent<HTMLInputELement>,
               index: number): void => {
  const newItems = this.state.items.slice(0, index).concat(
      this.state.items.slice(index + 1));
  this.setState({items: newItems});
}
```

Example: To-Do List (v2)

TodoApp – State

```
// Represents one item in the todo list.
type TodoItem = {
  name: string;
  completed: boolean;
};

// State of the app is the list of items and the text that the
// the user is typing into the new item field.
type TodoState = {
  items: TodoItem[];     // existing items
  newItemName: string;   // mirrors text in the field to add a new
                            name
                         //(need this for two reasons…)
};
```

TodoApp – Class

```
// Application that displays a to-do list.
export class TodoApp extends Component<{}, TodoState> {

  constructor(props: {}) {
    super(props);

    this.state = {items: [], newItemName: ""};
  }

  …
```

TodoApp – Render

```
// Return a UI with all the items and elements that allow them to
// add a new item with a name of their choice.
render = (): JSX.Element => {
  return (
    <div>
      <h2>To-Do List</h2>
      {this.renderItems()}
      <p>Check the item to mark it completed.</p>
      <label htmlFor="name">New item: </label>
        <input id="name" type="text"
               value={this.state.newItemName}
               onChange={this.doNewItemNameChange}/>
        <button type="button"
                onClick={this.doAddClick}>Add</button>
    </div>);
};
```

TodoApp – Add Click

```
// Called when the user clicks on the button to add the new item.
doAddClick = (_: MouseEvent<HTMLButtonElement>): void => {
  // Ignore the request if the user hasn't entered a name.
  const name = this.state.newItemName.trim();
  if (name.length === 0)
    return;

  // Cannot mutate this.state.items! Must make a new array.
  const newItems = this.state.items.concat(
      [{name: name, completed: false}]);
  this.setState({items: newItems, newItemName: ""});
                                                  //clear input box
};
```

TodoApp – New Name Change

```
// Called each time the text in the new item name field is changed.
doNewItemNameChange = (evt: ChangeEvent<HTMLInputElement>): void =>
{
  this.setState({newItemName: evt.target.value});
}
```

- Most event handlers are passed an event object
  - field "`evt.target`" stores the object that fired the event
  - hence, "`evt.target.value`" is the text in that input box

- Make sure no data on screen would disappear on re-render
  - must record the text the user typed into the field
    goes into the value={..} attribute of the input box
  - otherwise, render would produce an input box with no text

Other Events

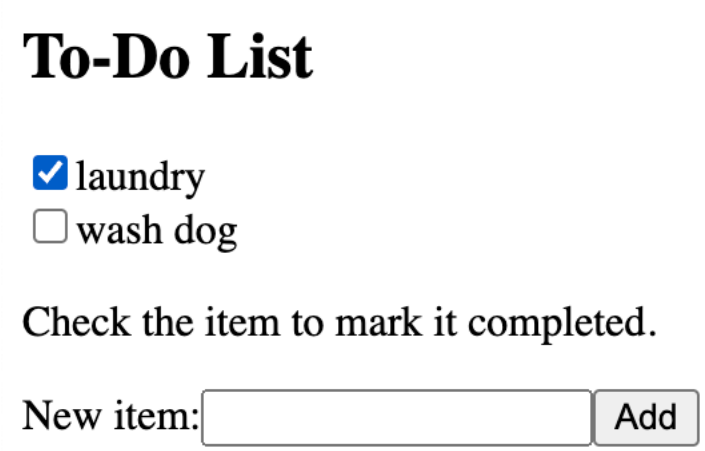
- Components should be just rendering & event handlers
  - our linter will enforce this

- Timers have events that fire after a given time
  - call to `setTimeout` invokes callback after a delay

Example: Auctions

More Complex UI

- To-Do List UI is basic
  - all of it easily fits in a single component (`TodoApp.tsx`)



- More complex UI can be too much code for one file
  - necessary to split it into multiple components

Recall: Other Properties of High-Quality Code

- Professionals are expected to write high-quality code
- Correctness is the most important part of quality
  - users **hate** products that do not work properly
- Also includes the following:
  - easy to understand
  - easy to change
  - modular

} via abstraction

Component Modularity

- Poor design to put all the app in one Component
  - it works, but is lacks properties of high-quality code
  - better to break it into smaller pieces (modular)

- Two ways to the UI into separate components:

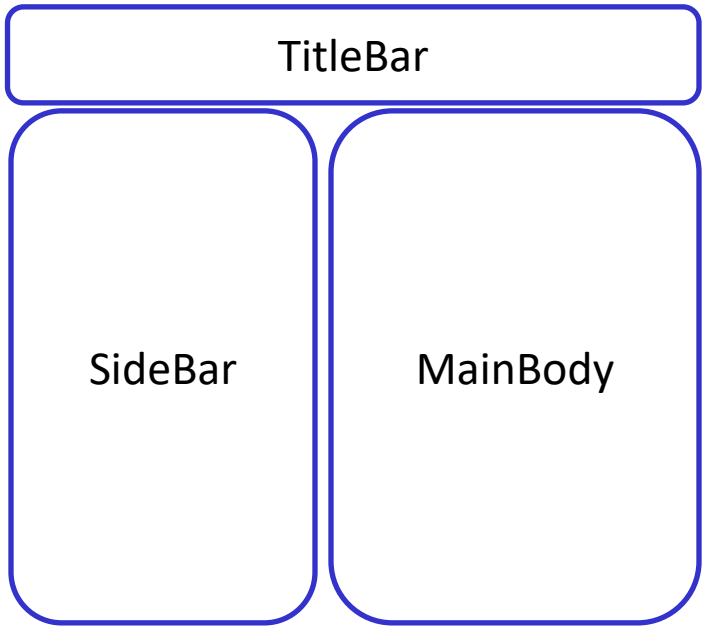
  1. Separate parts that are next to each other on screen

  2. Separate parts on the screen at different times

Component Modularity

- **Separate parts that are next to each other**

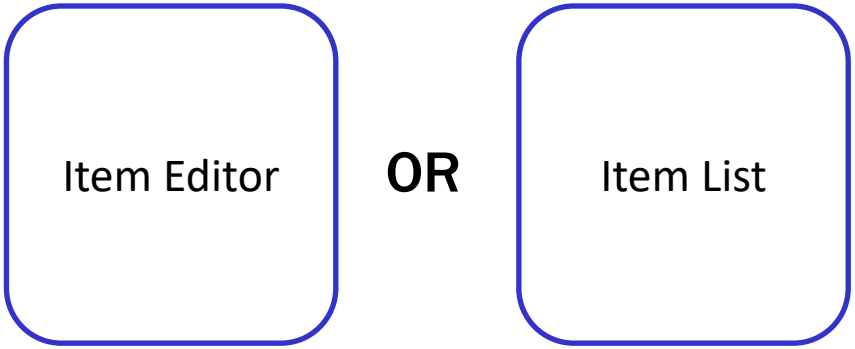
```
class App extends Component<..> {
  render = (): JSX.Element {
    return (<div>
        <TitleBar title={“My App”}/>
        <SideBar/>
        <MainBody/>
      </div>);
  };
}
```



Component Modularity

- Separate parts on the screen at different times

- App is always on the screen
  - App chooses which child component to display



  - sometimes it has an Editor child and sometimes not

Component Modularity

- **Separate parts on the screen at different times**

```
type AppState = {editItem: string | undefined};

class App extends Component<{}, AppState> {
  …
  render = (): JSX.Element {
    if (this.state.editItem !== undefined) {
      return <ItemEditor item={this.state.editItem}/>;
    } else {
      return <ItemList/>;
    }
  };
  …
}
```

Example: Auctions

Example: Auction UI

- Auction site has three different “pages”

Current Auctions

- Oak Cabinet — ends in 10 min
- Red Couch — ends in 15 min
- Blue Bicycle

New

New Auction

Name: Bob

Item: Table Lamp

...

Oak Cabinet

A beautiful solid oak cabinet. Perfect for any bedroom. Dimensions are 42” x 60”.

Current Bid: $250

Name: Fred

Bid: 251

Submit

Example: Auction UI

- Auction site has three different “pages”

- Need four different components:
  - Auction List: shows all the auctions (and Add button)
  - Auction Details: shows details on the auction (w Bid button)
  - New Auction: lets the user describe a new auction
  - **App**: decides which of these pages to show

Auction Client: `App.tsx`

- state needs to indicate which page to be showing

```
// Inv: 0 <= index < auctions.length
type Page = {kind: "list"} | {kind: "new"} |
            {kind: "details", index: number};

type AppState = {page: Page,
                 auctions: ReadonlyArray<Auction>};

export class App extends Component<{}, AppState> { … }
```

- What is `Page` an example of?

  it is an **inductive data type** (of the "enum" variety)

$$\textbf{type}\ \text{Page} := \text{list} \mid \text{new} \mid \text{details}(\text{n} : \mathbb{N})$$

Auction Client: App.tsx

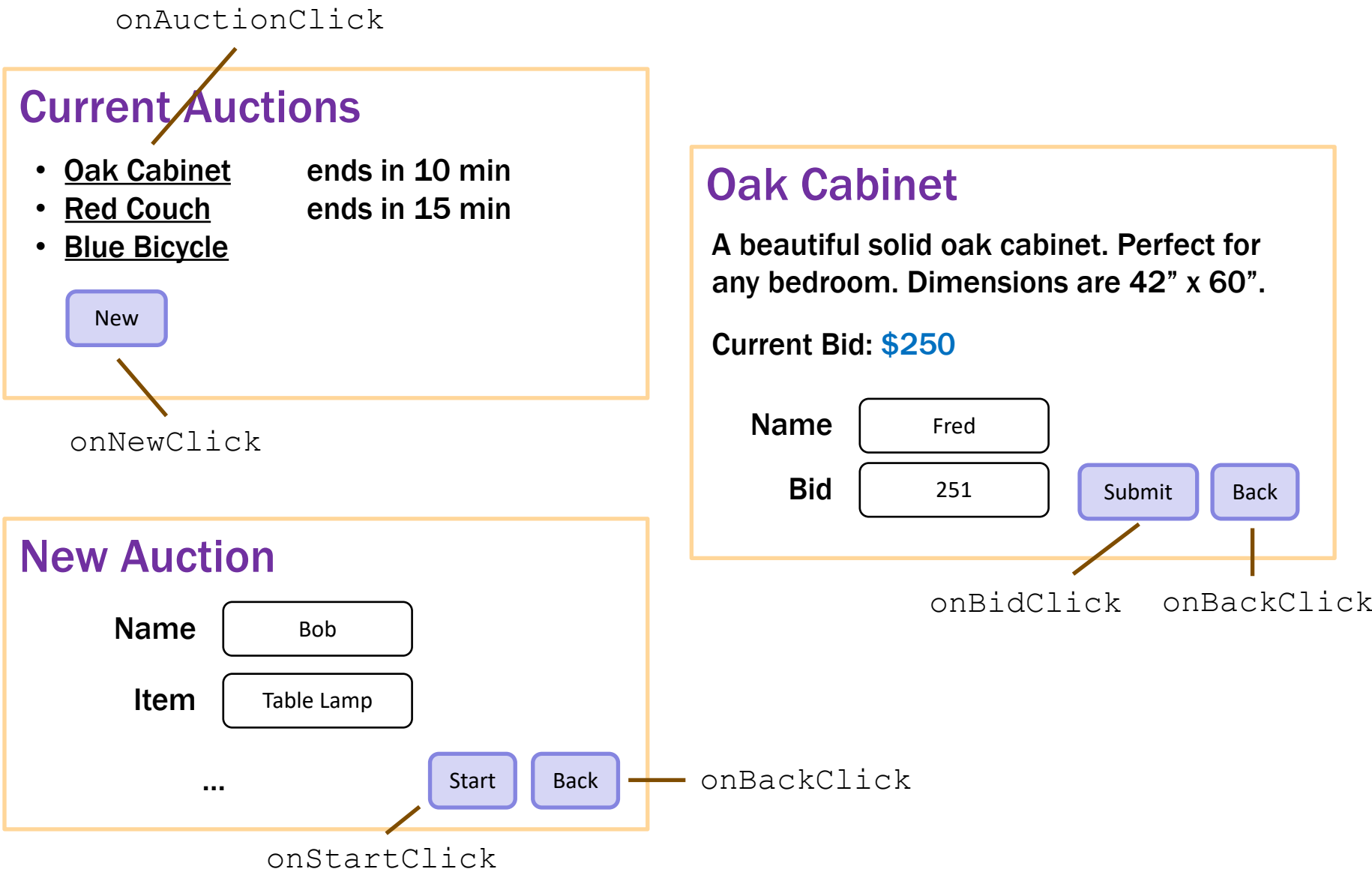
- render shows the appropriate UI

```
render = (): JSX.Element => {
  if (this.state.page.kind === "list") {
    return <AuctionList auctions={this.state.auctions}
                        onNewClick={this.doNewClick}
                        onAuctionClick={this.doAuctionClick}/>;

  } else if (this.state.page.kind === "new") {
    return <NewAuction onStartClick={this.doStartClick}
                       onBackClick={this.doBackClick}/>;

  } else {  // kind: "details"
    const index = this.state.page.index;
    const auction = this.state.auctions[index];
    return <AuctionDetails auction={auction}
onBidClick={(bidder, amt)=> this.doBidClick(index,bidder,amt}
onBackClick={this.doBackClick}/>;
  }
};
```

Example: Auction UI



Auction Client: App.tsx

- event handlers change what is shown

```
doNewClick = (): void => {
  this.setState({page:{kind:"new"}}); //show new auction page
};

doBackClick = (): void => {
  this.setState({page:{kind:"list"}});//show auction list page
};

doAuctionClick = (index: number): void => {
  // show details list page for the given auction
  const auction = this.state.auctions[index];
  this.setState({page: {kind: "details", index}});
};
```

Auction Client: `App.tsx`

- **the `App` component stores the auction list**

  easy to pass it down to subcomponents in their props

- **subcomponents cannot mutate the auction list!**

  they must invoke **callbacks** to have the `App` update the auction list

```
doStartClick = (info: NewAuctionInfo): void => {
  const maxBid = info.minBid - 1;
  const maxBidder = info.seller;
  const endTime = Date.now() + info.minutes * 60 * 1000;
  const auction = {name: info.name description: info.description,
                   seller: info.seller, maxBid, maxBidder, endTime};
  const auctions = this.state.auctions.concat([auction]);
  this.setState({page: {kind: "list"}, auctions});
};
doBidClick = (index: number, bidder: string, amount: number) => {
  const oldAuctionVal = this.state.auctions[index];
  const newAuctionVal = …;  // update the auction to have a new high bidder
  const auctions = this.state.auctions.slice(0, index)
      .concat([newAuctionVal])
      .concat(this.state.auctions.slice(index+1));
  this.setState({auctions, page:{kind: "details", index}});
};
```

Next Up: “Full Stack” (Client & Server)

- Stateful client: error in one method fails in another
  - bug in writing new state shows up when reading it
- Client-server: error in one part can fail in the other
  - bug in client shows up as server crash
  - bug in server shows up as client crash
- HW Squares - Final are the debugging assignments
  - necessary to understand all the parts of the code