CSE 331

Object-Oriented Programming

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Object-Oriented Programming

- We haven't done any OO this quarter
  - this week, we will see some reasons why!
- Plan for this week:
  - focus on topics that are good to know but not needed for HW
    - usually, mistakes you want to avoid
  - every lecture will include one related to OO

Subtypes

Subtypes of Concrete Types

- We initially defined types as sets

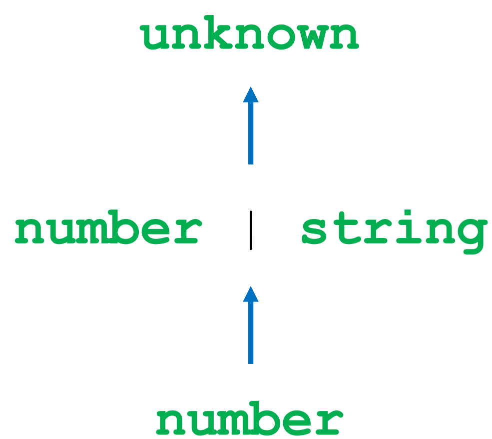
- In math, a **subtype** can be thought of as a **subset**
  - e.g., the even integers are a subtype of $\mathbb{Z}$
  - e.g., the numbers {1, 2, 3, 4, 5, 6} are a subtype of $\mathbb{Z}$
  - likewise, a superset would be a **supertype**

- Any even integer “is an” integer
  - “is a” is often (but not always) good intuition for subtypes

Subtypes of Concrete Types

- We initially defined types as sets

- In TypeScript, some subtypes are also subsets
  - `number` has a set of allowed values
  - it is a subtype of types that allow those values + more



Subtypes of Concrete Types

- We initially defined types as sets

- In TypeScript, some subtypes are also subsets
  - record types require certain fields but allow more
  - record type with a superset of the fields is a subtype

```
{name: string}
      ↑
{name: string, completed: boolean}
```

Subtyping Used by TypeScript

- TypeScript uses subtyping in function calls

```
const f = (s: number | string): number => { … };

const x: number = 3;
… f(x) …
```

  – types are not the same (`number` vs `number | string`)
  – subtype can be passed where super-type is expected
    any element of the subtype "is an" element of the super-type

- Similar rules in Java

Subtyping Used by TypeScript

- TypeScript uses subtyping in function calls

```
const f = (n: number): number => { … };

const x: number | string = f(3);
```

  - types are not the same (`number` vs `number | string`)
  - subtype can be returned where super-type is expected

    any element of the subtype “is an” element of the super-type

- Similar rules in Java

Subtyping Used by TypeScript

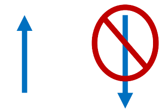
- TypeScript only sees the declared types
  - any other behavior is left to **reasoning**

- Example: invariants

```
// RI: 0 <= index < options.length
type OptionState = {
  options: string[],
  index: number
}
```

Subtyping Used by TypeScript

```
{options: string[], index: number}
```



```
OptionState
```

- `OptionState` **is a subtype of the bare record type**
  - **it is a record with those fields**
  - **but reverse is not true**

- **TypeScript will see these as the same**
  - **will let you pass the top where the bottom is expected**

    up to us to make sure this doesn't happen

Subtypes of Abstract Types

- Recall: ADTs are collections of functions
  - hide the concrete representation
  - pass functions that operate on the data
    - create, observe, mutate
- "Subtypes are subsets" does not work well here
  - set of all possible functions with ... yuck
- Would be nice to find a cleaner approach

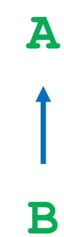
Subtypes Are Substitutable

- If B is a subtype of A, can send B where A is expected:

```
const f = (s: A): void => { … }
const g = (): B => { … }

const x: B = …;
f(x);                  // okay

const y: A = g();   // okay
```



  – okay to "substitute" a B where an A is expected

Subtypes Are Substitutable

- Subtypes are **substitutable** for supertype
  - this is the "Liskov substitution principle"
  - due to Barbra Liskov
- For ADTs, we use this as our definition of subtypes
  - (for concrete types, subsets are usually easier)

Subtypes of Abstract Types

- When is ADT B substitutable for A?

- Must satisfy two conditions:

  1. B must provide all the methods of A

     If A has a method "f", then B must have a method called "f"

  2. B's corresponding method must…

     must accept all the inputs that A's does

     must also promise everything in A's postcondition

     I.e., B must have the same or a **stronger spec**

Review: Strengthening a Specification

```
interface A {
  f: (x: number) => number

  // @requires x >= 0
  g: (x: number) => number
}
```

- Stronger specs allow more (or same) inputs
  - allowed argument types are supersets

```
interface B extends A {
  f: (x: number | string) => number
}
```

  - fewer requirements on arguments

```
interface C extends A {
  g: (x: number) => number     // x can be negative
}
```

Review: Strengthening a Specification

```
interface A {
  f: (x: number) => number

  // @requires x >= 0
  g: (x: number) => number
}
```

- Stronger specs promise more (or same) outputs
  - more specific return type (or thrown type)

```
interface D extends A {
  f: (x: number) => 0 | 1 | 2 | 3
}
```

Review: Strengthening a Specification

```
interface A {
  f: (x: number) => number

  // @requires x >= 0
  g: (x: number) => number
}
```

- Stronger specs promise more (or same) outputs
  - more specific return type (or thrown type)
  - more facts included in @returns and @effects

```
interface E extends A {
  // @requires x >= 0
  // @returns an even integer
  g: (x: number) => number
}
```

  - fewer objects listed in @modifies

Example: Rectangle and Square

- Is Square a subtype of Rectangle?
  - math intuition says yes
  - a square “is a” rectangle

- Let’s check this with substitutability…

Example: Immutable Rectangle and Square

```
interface Rectangle {
  getWidth: () => number,
  getHeight: () => number
}

// A rectangle with width = height
interface Square extends Rectangle {
  getSideLength: () => number
}
```

extra invariant
on abstract state
(an “abstract invariant”)

Yes

- Is `Square` substitutable for `Rectangle`?
  - allows the same inputs (none)
  - makes the same promises about outputs (numbers)
  - adds another promise: both methods return same number

Example: Mutable Rectangle and Square

```
interface Rectangle {
  getWidth: () => number,
  getHeight: () => number
  resize: (width: number, height: number) => void
}

// A rectangle with width = height
interface Square extends Rectangle {
  // @requires width = height
  resize: (width: number, height: number) => void
}
```

- **Is `Square` substitutable for `Rectangle`?** No!
  - allows fewer inputs to resize!

Example: Mutable Rectangle and Square

- None of these work:

weaker spec

```
// @requires width = height
resize: (width: number, height: number) => void

// @throws Error if width != height
resize: (width: number, height: number) => void
```

incomparable specs

```
// Sets height = width also
resize: (width: number , height: number) => void
```

- Mutation sometimes makes subtyping impossible
  - yet another reason to avoid it

Subclasses

Subclasses

- **Subclassing is a means of sharing code**
  - subclass gets parent fields & methods (unless overridden)

```
class Product {
  private String name;
  private int price;
  public String getName() {return name; }
  public int getPrice() { return price; }
}

class SaleProduct extends Product {
  private float discount;
  public int getPrice() {
    return (1 - discount) * super.getPrice();
  }
}
```

Subclasses

- **Subclassing does not guaranty subtyping relationship**

```java
class Product {
  public int getPrice() { ... }

  // @returns true iff obj's price < p's price
  public boolean isCheaperThan(Product p) {
    return getPrice() < p.getPrice();
  }
}

class WackyProduct extends Product {
  // @returns some boolean value
  public boolean isCheaperThan(Product p) {
    return false;
  }
}
```

Legal Java, but not a subtype

Subclasses

- Java subclassing is a means of sharing code
  - subclass gets parent fields & methods (unless overridden)
- Does not guarantee subtyping
  - up to you to check that method specs are stronger
- Java treats it as a subtype
  - will let you pass subclasses where superclass is expected
- Subclassing is a surprisingly dangerous feature
  - that's not the only reason…

Subclasses

- Subclassing is a surprisingly dangerous feature
- Subclassing tends to break modularity
  - creates tight coupling between super- and sub-class
  - often see the "fragile base class" problem

    changes to super class often break subclasses
- Let's see some Java examples…

Example 1: Tight Coupling

```
class Product {
  private int price;
  public int getPrice() { return price; }

  // @returns true iff obj's price < p's price
  public boolean isCheaperThan(Product p) {
    return getPrice() < p.getPrice();
  }
}

class SaleProduct extends Product {
  public int getPrice() {
    return (1 - discount) * super.getPrice();
  }
}
```

– looks okay so far…

Example 1: Tight Coupling

```
class Product {
  private int price;
  public int getPrice() { return price; }

  // @returns true iff obj's price < p's price
  public boolean isCheaperThan(Product p) {
    return this.price < p.price;
  }
}

class SaleProduct extends Product {
  public int getPrice() {
    return (1 - discount) * super.getPrice();
  }
}
```

Made it faster by eliminating a method call!

What's wrong?

Oops! Broke the subclass

Example 2: Tight Coupling

```java
class InstrumentedHashSet extends HashSet<Integer> {
  private static int count = 0;

  public boolean add(Integer e) {
    count += 1;
    return super.add(e);
  }

  public boolean addAll(Collection<Integer> c) {
    count += c.size();
    return super.addAll(c);
  }

  public int getCount() { return count; }
}
```

– **what could possibly go wrong?**

Example 2: Tight Coupling

```
InstrumentedHashSet S = new InstrumentedHashSet();
System.out.println(S.getCount());  // 0
S.addAll(Arrays.asList(1, 2));
System.out.println(S.getCount());  // 4?!?
```

- what does this print?

- **What is printed depends on `HashSet`'s `addAll`:**
  - **if it calls `add`, then this prints 4**
  - **if it does not call `add`, then this prints 2**
- **Also possible to be dependent on *order* of calls**

Subclassing Creates Tight Coupling

- Creates tight coupling between super- and sub-class
- Example 1: super-class needs to know about subclass
  - direct field access in parent breaks subclass
- Example 2: subclass needs to know about super-class
  - subclass dependent on which methods call each other
- But wait… There's more!

Example 3: Tight Coupling

```
class WorkList {
  // RI: len(names) = len(times) and total = sum(times)
  protected ArrayList<String> names;
  protected ArrayList<Integer> times;
  protected int total;

  public addWork(Job job) {
    addToLists(job.getName(), job.getTime());
    total += job.getTime();
  }

  protected addToLists(String name, int time) {
    names.add(name);
    times.add(time);
  }
}
```

Example 3: Tight Coupling

```
// Makes sure no task is too large compared to rest
class BalancedWorkList extends WorkList {
  protected addToLists(String name, int time) {
    if (times.size() <= 3 || 2*time < total)
      super.addToLists(name, time);  // okay
    } else {
      throw new ImbalancedWorkException(name, time);
    }
  }
}
```

– prevents item from being added if too big
– (also: this subclass is not a subtype!)

Example 3: Tight Coupling

```
class WorkList {
  // RI: len(names) = len(times) and total = sum(times)
  protected ArrayList<String> names;
  protected ArrayList<Integer> times;
  protected int total;

  public addWork(Job job) {
    int time = job.getTime();  // just one call
    total += time;
    addToLists(job.getName(), time);
  }
}
```

RI not true in method call

– reordering the updates breaks the subclass!
– subclass is using `total` that includes the new job

Example 3: Tight Coupling

- RI can be false in calls to non-public methods
  - only needs to hold at end of the public method

- Requires extra care to get it right
  - method is tightly coupled with the ones that call it
  - needs to know what is true in those methods
    - not enough to just know the RI

- Hard for multiple people to communicate this clearly
  - can be okay when it's all your code
  - very error prone when methods are written by others

Subclassing Creates Tight Coupling

- Creates tight coupling between super- and sub-class
  - direct field access can break subclass
  - subclass dependent on which methods call each other
  - subclass dependent no *order* of method class
  - subclass can be called when RI is false
- Often see the “fragile base class” problem
- Subclassing is a surprisingly dangerous feature!
  - up to you to verify subclass method specs are stronger
  - up to you to prevent tight coupling

Subclassing is Best Avoided

- Java advice: either design for subclassing or prohibit it
  - from Josh Bloch, author of (much of) the Java libraries
- We haven't used subclassing in TypeScript
  - didn't even describe how to do it!
    - we've just used classes as a quick way to create records
  - these problems are the main reason why we avoided it
- Subclassing is not necessary anyway
  - we have other ways to share code

Equality

Equity of User-Defined Types

- For any type, useful to know which are "the same"

- TypeScript "`===`" is not useful on records:

```
{a: 1} === {a: 1}  // false!
```

  - as in Java, this is "reference equality"
  - tells you if they refer to the same object in memory

- `deepStrictEquals` would work here
  - checks that the records have the same fields and values
  - but that also is not perfect…

Recall: Queue With Two Lists

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

  // AF: obj = concat(this.front, rev(this.back))
  readonly front: List<number>;
  readonly back: List<number>;
```

– two ways of representing the same abstract state:

```
{front: cons(1, cons(2, nil)), back: nil}  // = 1, 2
{front: nil, back: cons(2, cons(1, nil))}  // = 1, 2
```

– these should be considered equal!

Equality

- **Often useful / necessary to define your own `equal`**
  - **check if references point to records that are "the same"**

- **Sensible definition should act like "=" in math:**

  1. $\text{equal}(a, a) = T$ for any $a : A$ — reflexive
  2. $\text{equal}(a, b) = \text{equal}(b, a)$ for any $a, b : A$ — symmetric
  3. if $\text{equal}(a, b)$ and $\text{equal}(b, c)$, then $\text{equal}(a, c)$ for any … — transitive

  - **(311 alert: this is an "equivalence relation")**
  - **Java has two more rules for equals (see Java docs)**

Example: Duration

- **Define** Duration **representing an amount of time**

$$\textbf{type}\ \text{Duration} = \{\text{min} : \mathbb{Z}, \text{sec} : \mathbb{Z}\}\ \ \text{with}\ \ 0 \le \text{sec} < 60$$

  - **second part is a rep invariant**

- **Can define equality on** Duration **this way:**

$$\text{equal}(\{\text{min: m, sec: s}\}, \{\text{min: n, sec: t}\})\ \ :=\ \ (\text{m} = \text{n})\ \text{and}\ (\text{s} = \text{t})$$

  - **true iff these are the same amount of time**

    (wouldn't be true without the invariant)

Example: Duration

$$\text{equal}(\{\text{min: m, sec: s}\}, \{\text{min: n, sec: t}\}) \quad := \quad (m = n) \text{ and } (s = t)$$

- **Does this have the required properties?**
  - reflexive

$$\begin{aligned} &\text{equal}(\{\text{min: m, sec: s}\}, \{\text{min: m, sec: s}\}) \\ &\quad = (m = m) \text{ and } (s = s) && \textbf{def of } \text{equal} \\ &\quad = T \text{ and } T \\ &\quad = T \end{aligned}$$

proof by calculation
that it holds for any record

  - symmetric

$$\begin{aligned} &\text{equal}(\{\text{min: m, sec: s}\}, \{\text{min: n, sec: t}\}) \\ &\quad = (m = n) \text{ and } (s = t) && \textbf{def of } \text{equal} \\ &\quad = (n = m) \text{ and } (t = s) \\ &\quad = \text{equal}(\{\text{min: n, sec: t}\}, \{\text{min: m, sec: s}\}) && \textbf{def of } \text{equal} \end{aligned}$$

Example: Duration

$$\text{equal}(\{\text{min: m, sec: s}\}, \{\text{min: n, sec: t}\}) \quad := \quad (m = n) \text{ and } (s = t)$$

- Does this have the required properties?
  - reflexive — yes
  - symmetric — yes
  - transitive — also yes (but a little long for a slide)

- Good evidence that this is a reasonable definition

Non-Example: "==" in JavaScript

```
0 == "0"        true
0 == ""         true
0 == " "        true
```

- **Does this have the required properties?**
  - reflexive yes
  - symmetric yes
  - transitive no! ("" != " ")

- **Good evidence that this is not a reasonable definition**

Example: List Equality

- **Can define equality on List type this way:**

equal(nil, nil)	:=	T	
equal(nil, cons(b, R))	:=	F	
equal(cons(a, L), nil)	:=	F	
equal(cons(a, L), cons(b, R))	:=	F	if $a \neq b$
equal(cons(a, L), cons(b, R))	:=	equal(L, R)	if $a = b$

- **Checks that the values in the list are all the same**
  - **this is a definition, so we can only check it on examples…**

$$
\begin{aligned}
\text{equal}(\boxed{1} \to \boxed{2}\,,\ \boxed{1} \to \boxed{2}) &= \text{equal}(\boxed{2}\,,\ \boxed{2}) \\
&= \text{equal}(\text{nil}, \text{nil}) \\
&= \text{T}
\end{aligned}
$$

Example: List Equality

- **Can define equality on List type this way:**

equal(nil, nil)	:=	T	
equal(nil, cons(b, R))	:=	F	
equal(cons(a, L), nil)	:=	F	
equal(cons(a, L), cons(b, R))	:=	F	if $a \neq b$
equal(cons(a, L), cons(b, R))	:=	equal(L, R)	if $a = b$

- **Checks that the values in the list are all the same**
  - **this is a definition, so we can only check it on examples…**

$$\text{equal}(\boxed{1} \rightarrow \boxed{2}, \boxed{1} \rightarrow \boxed{3}) = \text{equal}(\boxed{2}, \boxed{3})$$
$$= \text{F}$$

Example: List Equality

- **Can define equality on List type this way:**

equal(nil, nil)	:=	T	
equal(nil, cons(b, R))	:=	F	
equal(cons(a, L), nil)	:=	F	
equal(cons(a, L), cons(b, R))	:=	F	if $a \neq b$
equal(cons(a, L), cons(b, R))	:=	equal(L, R)	if $a = b$

- **Has all three required properties**
  - **how would we prove this holds for any list?** induction

Recall: Subtypes of Concrete Types

- We initially defined types as sets
- In math, a **subtype** can be thought of as a **subset**
  - e.g., the even integers are a subtype of $\mathbb{Z}$
  - e.g., the numbers {1, 2, 3, 4, 5, 6} are a subtype of $\mathbb{Z}$
  - likewise, a **superset** would be a **supertype**
- Any even integer “is an” integer
  - “is a” is often (but not always) good intuition for subtypes

Recall: Subtypes of Abstract Types

- Subtypes are **substitutable** for supertype
  - this is the "Liskov substitution principle"
  - due to Barbra Liskov

- For ADTs, we use this as our definition of subtype

- When is ADT B substitutable for A?

  1. B must provide all the methods of A

     If A has a method "f", then B must have a method called "f"

  2. B's corresponding method spec must be stronger than A's

     must accept all the inputs that A's does

     must also promise everything in A's postcondition

Example: Duration Again

```
// Represents an amount of time measured in seconds
class Duration {

  // RI: 0 <= sec < 60
  // AF: obj = 60 * this.min + this.sec
  readonly min: number;
  readonly sec: number;

  equal = (d: Duration): boolean => {
    return this.min === d.min && this.sec === d.sec;
  };

  …
```

– **defines `Duration` as an ADT instead**

  `getMinutes` and `getSeconds` methods not shown

  `equal` still makes sense, just as before

Example: NanoDuration

- **Suppose a subclass also measures nanoseconds**

```
class NanoDuration extends Duration {
  // min: number (inherited)
  // sec: number (inherited)
  readonly nano: number;

  …
```

- **How should we define `equal`?**
  - **remember that it takes an argument of type `Duration`**

    we cannot accept fewer arguments

Example: NanoDuration

```
class NanoDuration extends Duration {

  // min: number (inherited)
  // sec: number (inherited)
  readonly nano: number;

  equal = (d: Duration): boolean => {
    if (d instanceof NanoDuration) {
      return this.min === d.min &&
             this.sec === d.sec &&
             this.nano === d.nano;
    } else {
      return false;
    }
  };
```

Must take `Duration` argument to be a subtype

No! It lacks symmetry

– **does this have the three required properties?**

Example: NanoDuration

```
const d = new Duration(2, 10);
const n = new NanoDuration(2, 10, 300);

console.log(n.equal(d));   // false
console.log(d.equal(n));   // true!
```

- `NanoDuration` **is only equal to other** `NanoDuration`**s**
- `Duration` **can be equal to a** `NanoDuration`
  if they have the same minutes and seconds

Example: NanoDuration

```
class NanoDuration extends Duration {

  // min (inherited)
  // sec (inherited)
  readonly nano: number;

  equal = (d: Duration): boolean => {
    if (d instanceof NanoDuration) {
      return this.min === d.min &&
             this.sec === d.sec &&
             this.nano === d.nano;
    } else {
      return this.min == d.min && this.sec == d.sec;
    }
  };
```

No! It lacks transitivity

– fixes symmetry! all good now?

Example: NanoDuration

```
const n1 = new NanoDuration(2, 10, 300);
const d = new Duration(2, 10);
const n2 = new NanoDuration(2, 10, 400);

console.log(n1.equal(d));   // true
console.log(d.equal(n2));   // true
console.log(n1.equal(n2));  // false!
```

– **transitivity requires** `n1` **to equal** `n2` **(but it doesn't)**

Subclasses and Equals Don't Always Mix

- No good solution to this problem!
  - inherent tension between subtyping and equality

    subtyping wants subclasses to behave the same

    equality wants to treat them differently (using extra information)

- This is a general problem for "binary operations"
  - equality is just one example

- Real issue may be that `NanoDuration` isn't a subtype
  - subclass does not mean subtype
  - (would have seen this if we documented the ADT properly)

Example: NanoDuration Again

- Suppose a subclass also measures nanoseconds

```
// Represents an amount of time in nanoseconds
class NanoDuration extends Duration {

  // RI: 0 <= sec < 60 and 0 <= nano < 10000
  // AF: obj = 60,000,000 * this.min +
  //           1,000,000 * this.sec +
  //           this.nano
  readonly nano: number;

}
```

- Abstract states of the two types are different
  - time in seconds vs nanoseconds
  - abstract states of subtypes would need to be subtypes

Constructors

Public Constructors

- Most Java classes have public constructors
  - e.g., create an `ArrayList` with "`new ArrayList<String>()`"
- For our ADTs, we didn't do this
  - class was hidden (not exported)
  - we exported a "factory function" that used the constructor

    e.g., `makeSortedNumberSet`
  - this was not accidental…
- Constructors have undesirable properties
  - surprisingly error-prone
  - several important limitations

Recall: Tight Coupling (Example 3)

```
class WorkList {
  // RI: len(names) = len(times) and total = sum(times)
  protected ArrayList<String> names;
  protected ArrayList<Integer> times;
  protected int total;

  public addWork(Job job) {
    int time = job.getTime();  // just one call
    total += time;
    addToLists(job.getName(), time);
  }
}
```

RI is not true in method call!

Method Calls from Constructors

- Any method call from a constructor is dangerous!

- Almost always calling with RI false
  - usually, the RI does not hold until all fields are assigned
    - typically, that is the last line of the constructor
  - hence, any methods are called with the RI still false

- Asking for trouble!
  - method needs to know that some parts of RI may be false
  - eventually, someone changing code will mess this up
  - better to avoid method calls in the constructor

Limitations of Constructors

- Constructor is called *after* the object is created
  - can't decide, in the constructor, not to create it

- Limitations of constructors

  1. Cannot return an existing object

  2. Cannot return a different class

  3. Does not have a name!

Singleton

- Factory functions can return an existing object
- Common case: there is only one instance!
  - factory function can avoid creating new objects each time
  - called the "singleton" design pattern
- Example from HW5…

Example: Singleton in HW5

```
// @returns ColorList containing all known colors
export const makeSimpleColorList = (): ColorList => {
  return new SimpleColorList(COLORS);
}
```

– every object returned is the same
– no need to make more than one

```
const simpleColorList = new SimpleColorList(COLORS);

// @returns ColorList containing all known colors
export const makeSimpleColorList = (): ColorList => {
  return simpleColorList;
}
```

Note: only allowed because `SimpleColorList` is **immutable**

Returning a Subtype

- Factory functions can return a subtype
  - declared to return `A` but returns subtype `B` instead
  - allowed since every `B` is an `A`

- Example:

```
// @returns an empty NumberSet that can be used to
//     store numbers between min and max (inclusive)
const makeNumberSet = (min: number, max: number): NumberSet => {
  if (0 <= min && max <= 100) {
    return makeArrayNumberSet();  // only supports small sets
  } else {
    return makeSortedNumberSet(); // use a tree instead
  }
}
```

Multiple Constructors

- **Java classes allow multiple constructors**

```
class HashMap {
  public HashMap() { … }  // initial capacity of 16
  public HashMap(int initialCapacity) { … }
}
```

- **TypeScript classes do not, but you can fake it with *optional* arguments**

```
class HashMap {
  constructor(initialCapacity?: number) { ... }
}
```

Constructors Have No Name

- Do not get to name constructors
  - in Java, same name as the class
  - in TypeScript, called “constructor”

- Names are useful

  1. Let you distinguish between different cases
     - use names to distinguish cases that otherwise look the same

  2. Let you explain what it does
     - the only thing you know the client will read!

Example: Distinguishing Constructors

- JavaScript's Array has multiple constructors

```
new Array()             // creates []
new Array(a1, …, aN)    // creates [a1, …, aN]
new Array(2)            // creates [undefined, undefined]
```

  – what does "`new Array(a1)`" return when `a1` is a number?
  – how to make a 1-element array containing just `a1`

```
const A = new Array(1);
A[0] = a1;
```

  – don't have a name to distinguish these cases!

Example: Distinguishing Constructors

- Factory Functions have names
  - allow us to distinguish these cases

```
// @returns []
const makeEmptyArray = (): Array => { … };

// @returns A with A.length = len and
//      A[j] = undefined for any 0 <= j < len
const makeArray = (len: number): Array => { … };

// @returns [args[0], …, args[N-1]]
const makeArrayContaining = (...): Array => { … };
```

Example: Distinguishing Constructors

- Factory Functions have names
  - allow us to distinguish these cases

```
// @returns []
const makeEmptyArray = (): Array => { … };

// @returns A with A.length = len and
//      A[j] = undefined for any 0 <= j < len
const makeArray = (len: number): Array => { … };

// @returns A with A.length = len and
//      A[j] = val for any 0 <= j < len
const makeFilledArray =
    (len: number, val: number): Array => { … };
```

Be very, very careful…
Type checker won't notice if client mixes these up!

Argument Order Bugs

- Some famous bugs due to mixing up argument order!
- If you program long enough, you will see this one
  - … and just about every other bug

Use Records to Force Call-By-Name

- Can use a record to make clients type names

```
// @returns A with A.length = len and
//     A[j] = val for any 0 <= j < len
const makeFilledArray =
    (desc: {len: number, value: number}): Array
```

  - takes one argument, not two
  - client writes "`makeFilledArray({len: 3, value: 0})`"

- Think about mistakes clients might make
  - be paranoid when debugging will be painful

More Design Patterns

Recall: Design Patterns

- Introduced in the book of that name
  - written by the "Gang of Four"

    Gamma, Helm, Johnson, Vlissides
  - worked in C++ and SmallTalk

- Found that they independently developed many of the same solutions to recurring problems
  - wrote a book about them
  - required at least three real-world uses to be included

- Many are solutions to problems with OO languages
  - authors worked in C++ and SmallTalk

Parts of a Design Patterns

Each pattern in the book includes

- Problem to be solved
- Description of the solution
- Name of the pattern

Java Example: Iterator

- Java Collections use the Iterator Design Pattern
  - enumerate a collection while hiding data structure details
  - return another ADT that outputs the items
    - that object knows how to walk through the data structure
    - operations for retrieving the current item and moving on to the next one

- Clever idea that is now used everywhere
  - I remember when C++ introduced iterators
  - huge improvement over code we were writing before

Categories of Design Patterns

The book has three categories of patterns

- **Creational**: factory function, factory object, builder, prototype, singleton, ...
- **Structural**: adapter, bridge, composite, decorator, façade, flyweight, proxy
- **Behavioral**: command, interpreter, iterator, mediator, observer, state, strategy, visitor, ...
  - we will not cover all, just some highlights

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  – green = mentioned already

Creational Patterns

- One third of the patterns deal with object creation
- We saw why last time: constructors are terrible
  - surprisingly error-prone
  - several important limitations
    1. Cannot return an existing object
    2. Cannot return a different class
    3. Does not have a name!
- Already saw factory functions and singleton
  - yet we still need more!

Creational Pattern: Builder

- **Object that helps with creation of another object**
  - constructor / factory requires you to give info all at once
  - builder lets you describe what you want bit by bit

- **Java Example:** `StringBuilder`

```
StringBuilder buf = new StringBuilder();
buf.append("Total distance: ");
buf.append(distance);
buf.append(" meters.");
return buf.toString();
```

  - each call adds more text / number to the final string
  - we can't do this with strings because strings are *immutable*

Creational Pattern: Builder

- Object that helps with creation of another object
  - constructor / factory requires you to give info all at once
  - builder lets you describe what you want bit by bit

- Good pairing: mutable Builder for an immutable type
  - must avoid aliasing with the mutable builder

    e.g., never use it as a key in a BST or Map
  - immutable object can be shared arbitrarily

    no worries about aliasing
  - only need to be extra careful with the mutable part

Creational Pattern: Builder

- Builder is often written like this:

```
class FooBuilder {
  …
  public FooBuilder setX(int x) {
    this.x = x;
    return this;
  }
  …
  public Foo build() { … }
}
```

  – can then use them like this

```
Foo f = new FooBuilder().setX(1).setY(2).build();
```

avoids worries about argument order

Recall: Argument Order Bugs

```
// @returns A with A.length = len and
//      A[j] = val for any 0 <= j < len
const makeFilledArray =
    (len: number, val: number): Array => { … };
```

Be very, very careful…
Type checker won't notice if client mixes these up!

- Some famous bugs due to mixing up argument order!
- If you program long enough, you will see this one
- Can fix with a record argument or a Builder
  - Java does not have record types, so we need a builder

Argument Builder

```
// Returns an array with length & value given in args.
public Integer[] makeFilledArray(args: Args) { … }

class Args {
  public int length;
  public int value;
}

Args args = new Args();
args.length = 10;
args.value = 5;
… = makeFilledArray(args);
```

– **code using the function is now more verbose…**

  can make this easier by giving them a Builder

Argument Builder

```
// Returns an array with length & value given in args.
public Integer[] makeFilledArray(args: Args) { … }

class ArgsBuilder {
  …
  public ArgsBuilder setLength(int length) {
    this.length = length;
    return this;
  }
  …
  public Args toArgs() { … }
}

… = makeFilledArray(new ArgsBuilder()
    .setLength(10).setValue(5).toArgs());
```

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- **Behavioral**: command, interpreter, iterator, mediator, observer, state, strategy, visitor, ...
  - green = mentioned already

Structural Pattern: Adapter

- Mentioned this one in lecture 3
- In Java, these two classes are not interoperable:

```
interface Duration {
  int getMinutes();
  int getSeconds();
}

interface AmountOfTime {
  int getMinutes();
  int getSeconds();
}
```

  – cannot pass one where the other is expected

Structural Pattern: Adapter

- Mentioned this one in lecture 3

- Get around this by creating an adapter

```
class DurationAdapter implements AmountOfTime {
  private Duration d;

  public DurationAdapter(Duration d) {
    this.d = d;
  }

  int getMinutes() { return d.getMinutes(); }
  int getSeconds() { return d.getSeconds(); }
}
```

  – makes a `Duration` into an `AmountOfTime`

Structural Pattern: Adapter

- Adapters are often needed with nominal typing
  - design pattern working around a language issue

- With structural typing, these two interoperate:

```
type Duration = {min: number, sec: number};

type AmountOfTime = {min: number, sec: number};
```

  - can pass either where the other is expected
  - not an issue of concrete vs abstract

    still interoperable if we have `getMinutes` and `getSeconds` methods

Categories of Design Patterns

The book has three categories of patterns

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- **Behavioral**: command, interpreter, iterator, mediator, observer, state, strategy, visitor, ...
  - green = mentioned already

Trees

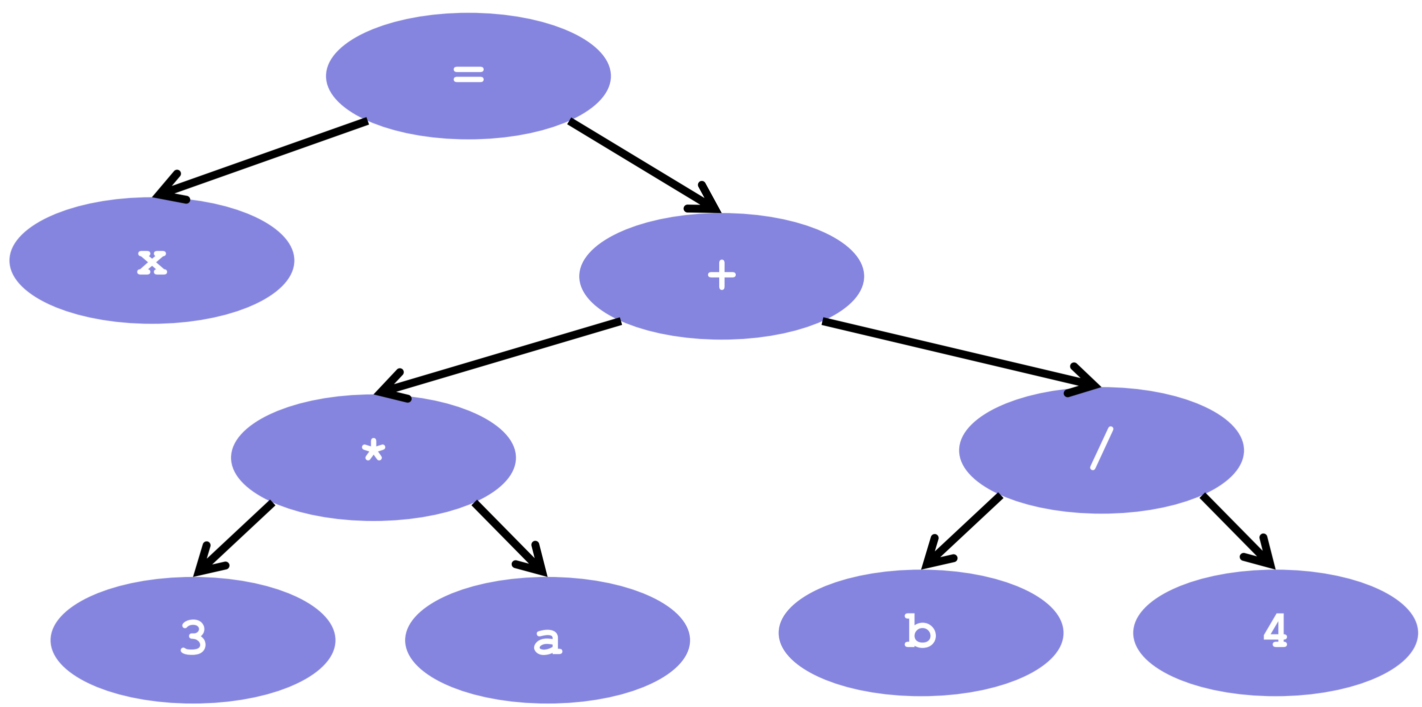
- Trees are inductive data types
  - anything with a constructor that has 2+ recursive arguments

    HW8 tree (Square) has 4 recursive arguments

- They arise frequently in practice
  - HTML: used to describe UI
  - JSON: used for client/server communication
  - parse trees: represent code

Parse Tree

- Output of parsing is a tree
  - encodes the order of operations
- Example: parse of "`x = a * 3 + b / 4`"



Parse Tree

- **Output of parsing is a tree**
  - **records the order of operations**

- **Parse tree is an inductive data type**

$$
\begin{aligned}
\textbf{type}\ \text{Expression} := \ & \text{variable}(\text{name}: \mathbb{S}^*) \\
| \ & \text{constant}(\text{val} : \mathbb{Z}) \\
| \ & \text{plus}(\text{left} : \text{Expr}, \text{right} : \text{Expr}) \\
| \ & \text{times}(\text{left} : \text{Expr}, \text{right} : \text{Expr}) \\
| \ & \text{divide}(\text{left} : \text{Expr}, \text{right} : \text{Expr}) \\
| \ & \text{assign}(\text{name} : \mathbb{S}^*, \text{value} : \text{Expr})
\end{aligned}
$$

  - **parse of "`x = a * b + c / d`"**

assign("x", plus(times(constant(3), variable("a")),
divide(variable("b"), constant(4))))

Operations on Parse Trees

- Compilers perform various operations on expressions
  - type check
  - evaluate
  - code generation

- Each operation defined for each type of expression

Type of Expr

Operation		Variable	Plus	Times
	type check			
	evaluate			
	code gen			

Operations on Parse Trees

- Need to write code for each box
  - each case is slightly different
- Two reasonable ways to organize into files
  - file per expression type: Interpreter pattern
  - file per operation: Procedural pattern

Type of Expr

Operation		Variable	Plus	Times
	type check			
	evaluate			
	code gen			

Interpreter Pattern

```
interface Expr {
  typeCheck = (c: Context) => Type,
  evaluate = (c: Context) => number | undefined,
  generate = (c: Context) => List<Instruction>
}

class Variable implements Expr {
  name: string;
  typeCheck = (c: Context): Type => {
    return c.get(this.name);
  }
  evaluate = (c: Context): number | undefined => {
    return undefined;
  }
  …
}
```

- **Each type of expression is a class**

Interpreter Pattern

```
interface Expr {
  typeCheck = (c: Context) => Type,
  evaluate = (c: Context) => number | undefined,
  generate = (c: Context) => List<Instruction>
}
```

- Easy to add new types of expression
  - new subtype of `Expr`
  - goes into its own file

- Hard to add new operations
  - new method of `Expr`
  - changes *every* file

Procedural Pattern

```
interface Procedure<R> {
  processVar = (v: Variable, c: Context) => R,
  processConst = (n: Constant, c: Context) => R,
  …
}

class TypeChecker implements Procedure<boolean> {
  processVar = (v: Variable, c: Context): boolean => {
    return c.has(v.name);
  }
  processConst = (n: Constant, c: Context): boolean => {
    return true;
  }
  …
}
```

- Each type of procedure is a class
  - one method for each type of expression

Procedural Pattern

```
interface Procedure<R> {
  processVar = (v: Variable, c: Context) => R,
  processConst = (n: Constant, c: Context) => R,
  …
}
```

- Easy to add new types of operations
  - new subtype of `Procedure`
  - goes into its own file

- Hard to add new expressions
  - new method of `Procedure`
  - changes *every* file

Interpreter vs Procedural Pattern

- Both patterns are reasonable
  - best choice is problem-dependent

    for a compiler, I prefer the procedural pattern

- But there is a problem with Procedural in OO
  - suppose `e` is an `Expr` but we don't know which one
  - how do we call the right method?

    could be `processVar`, `processConst`, `processPlus`, …

Problems with Procedural Pattern in OO

```
const process = (p: Procedure, e: Expr, c: Context) => {
  if (e instanceof Variable) {
    p.processVar(e, c);
  } else if (e instanceof Constant) {
    p.processConst(e, c);
  } else if (e instanceof Plus) {
    p.processPlus(e, c);
  } else …
}
```

- Not great, Bob!
  - code is slow
  - will call it enough times that this will matter
- There is a solution, but… buckle up!

Dynamic Dispatch (good case in Java)

```
interface Expr {
  boolean typeCheck(Context c);
}

class Variable implements Expr {
  public boolean typeCheck(Context c) { … }
}

class Constant implements Expr {
  public boolean typeCheck(Context c) { … }
}
```

- Java / TypeScript (or any OO) makes this case easy

```
Expr e = …
e.typeCheck(c);           // e could be any Expr
```

  – automatically "dispatches" to the right method

Dynamic Dispatch (bad case in Java)

```
interface Procedure<R> {
  R process(Variable v, Context c);
  R process(Constant n, Context c);
  …
}
```

overloading

```
class TypeChecker implements Procedure<Boolean> {
  Boolean process(Variable v, Context c) { … }
  Boolean process(Constant c, Context c) { … }
  …
}
```

- **This is impossible in Java:**

```
TypeChecker t = new TypeChecker();
Expr e = …
t.process(e, c);          // e could be any Expr
```

Dynamic Dispatch (bad case in Java)

- **This is impossible in Java:**

```
TypeChecker t = new TypeChecker();
Expr e = …
t.process(e, c);          // e could be any Expr
```

- **Need to put "`e`" before "`.`" to get dynamic dispatch**
  - here's how we do that… (gulp)

Double Dispatch

```
interface Procedure<R> {
  R process(Variable v, Context c);
  R process(Constant n, Context c);
  …
}
interface Expr {
  R perform(Procedure<R> p, Context c);
}
class Variable implements Expr {
  public R perform(Procedure<R> p, Context c) {
    p.process(this, c);
  }                                  calls process(Variable, Context)
}
class Constant implements Expr {
  public R perform(Procedure<R> p, Context c) {
    p.process(this, c);
  }                                  calls process(Constant, Context)
}
```

Double Dispatch

```
interface Procedure<R> {
  R process(Variable v, Context c);
  R process(Constant n, Context c);
  …
}
interface Expr {
  R perform(Procedure<R> p, Context c);
}
```

- We can now do this

```
Process p = new TypeChecker();
Expr e = …
e.perform(p, c);          // e could be any Expr
```

  - calls `Expr.perform`, which calls `TypeChecker.process`
  - two function calls is still faster than all the “`if`”s

Double Dispatch

- This works, but… why so hard?

- Other languages just let you do this:

```
Process p = new TypeChecker();
Expr e = …
p.process(e, c);          // e could be any Expr
```

  – or even more general "multiple dispatch" cases
  – use a better language?

Traversing Trees

- Same idea is used to traverse trees

type Expression := variable(name: $\mathbb{S}^*$)
| constant(val : $\mathbb{Z}$)
| plus(left : Expr, right : Expr)
| times(left : Expr, right : Expr)
| divide(left : Expr, right : Expr)
| assign(name : $\mathbb{S}^*$, value : Expr)

  - parse of "`x = 3 * a + b / 4`"

assign("x", plus(times(constant(3), variable("a")),
divide(variable("b"), constant(4)))

  - would like to process ("visit") each node in this tree

Visitor Pattern

```
interface ExprVisitor {
  visitVariable = (v: Variable) => void,
  visitConstant = (n: Constant) => void,
  visitPlus = (p: Plus) => void,
  …
}

interface Expr {
  // Visits this node and all its children.
  accept = (v: ExprVisitor) => void
}

class Variable implements Expr {
  name: string;
  accept = (v: ExprVisitor): void => {
    v.visitVariable(this);
  }
}

…
```

Visitor Pattern

- **Combines double dispatch with tree traversal**

```
class Plus implements Expr {
  left: Expr;
  right: Expr;

  accept = (v: ExprVisitor): void => {
    left.accept(v);
    right.accept(v);
    v.visitVariable(this);
  }
}
```

  - **traverses children before visiting parent**

Visitor Pattern

```
p.accept(v)
  t.accept(v)
    h.accept(v)
      v.visitConstant(h)
    a.accept(v)
      v.visitVariable(a)
    v.visitTimes(t)
  d.accept(v)
    …
    v.visitDivide(f)
  v.visitPlus(p)
```