CSE 331
Software Design & Implementation

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Design Patterns, Part 1
(Based on slides by Mike Ernst, Dan Grossman, David Notkin, Hal Perkins, Zach Tatlock)
Outline

• Introduction to design patterns

• Creational patterns (constructing objects)

Next lecture:

• Structural patterns (controlling heap layout)

• Behavioral patterns (affecting object semantics)
What is a design pattern?

A standard solution to a common programming problem
- A design or implementation structure that achieves a particular purpose
- A high-level programming idiom

A technique for making code more flexible
- Reduce coupling among program components

Shorthand description of a software design
- Well-known terminology improves communication/documentation
- Makes it easier to “think to use” a known technique

A few simple examples....
Example 1: Encapsulation (data hiding)

Problem: Exposed fields can be directly manipulated
  – Violations of the representation invariant
  – Dependences prevent changing the implementation

Solution: Hide some components
  – Constrain ways to access the object

Disadvantages:
  – Interface may not (efficiently) provide all desired operations to all clients
  – Indirection may reduce performance
Example 2: Subclassing (inheritance)

Problem: Repetition in implementations
  - Similar abstractions have similar components (fields, methods)

Solution: Inherit default members from a superclass
  - Select an implementation via run-time dispatching

Disadvantages:
  - Code for a class is spread out, and thus less understandable
  - Run-time dispatching introduces overhead
  - Hard to design and specify a superclass [as discussed]
Example 3: Iteration

Problem: To access all members of a collection, must perform a specialized traversal for each data structure
  – Introduces undesirable dependences
  – Does not generalize to other collections

Solution:
  – The *implementation* performs traversals, does bookkeeping
  – Results are communicated to clients via a standard interface (e.g., `hasNext()`, `next()`)

Disadvantages:
  – Iteration order fixed by the implementation and not under the control of the client
Example 4: Exceptions

Problem:
- Errors in one part of the code should be handled elsewhere
- Code should not be cluttered with error-handling code
- Return values should not be preempted by error codes

Solution: Language structures for throwing and catching exceptions

Disadvantages:
- Code may still be cluttered
- Hard to remember and deal with code not running if an exception occurs in a callee
- It may be hard to know where an exception will be handled
Example 5: Generics

Problem:
- Well-designed (and used) data structures hold one type of object

Solution:
- Programming language checks for errors in contents
- `List<Date>` instead of just `List`

Disadvantages:
- More verbose types
Why (more) design patterns?

Advanced programming languages like Java provide many powerful constructs – subtyping, interfaces, rich types and libraries, etc.

- But it’s not enough to “know everything in the language”
- Still many common problems not easy to solve

Design patterns are intended to capture common solutions / idioms, name them, make them easy to use to guide design

- For high-level design, not specific “coding tricks”

They increase your vocabulary and your intellectual toolset

Do not overuse them

- Not every program needs the complexity of advanced design patterns
- Instead, consider them to solve reuse/modularity problems that arise as your program evolves
Why should you care?

You could come up with these solutions on your own
  - You shouldn't have to!

A design pattern is a known solution to a known problem
  - A concise description of a successful “pro-tip”
Origin of term

The “Gang of Four” (GoF)

- Gamma, Helm, Johnson, Vlissides

Found they shared a number of “tricks” and decided to codify them

- A key rule was that nothing could become a pattern unless they could identify at least three real [different] examples
- Done for object-oriented programming
  - Some patterns more general; others compensate for OOP shortcomings
  - But any “paradigm” should have design patterns
Patterns vs. patterns

The phrase *pattern* has been wildly overused since the GoF patterns have been introduced.

Misused as a synonym for “[somebody says] X is a good way to write programs.”

- And “anti-pattern” has become a synonym for “[somebody says] Y is a bad way to write programs.”

GoF-style patterns have richness, history, language-independence, documentation and thus (most likely) far more staying power.
An example GoF pattern

For some class $C$, guarantee that at run-time there is exactly one instance of $C$
  – And that the instance is globally visible

First, why might you want this?
  – What design goals are achieved?

Second, how might you achieve this?
  – How to leverage language constructs to enforce the design

A pattern has a recognized name
  – This is the Singleton Pattern
Possible reasons for Singleton

- One RandomNumber generator
- One KeyboardReader, PrinterController, etc...
- Have an object with fields/properties that are “like public, static fields” but you can have a constructor decide their values
  - Maybe strings in a particular language for messages

- Make it easier to ensure some key invariants
  - There is only one instance, so never mutate the wrong one

- Make it easier to control when that single instance is created
  - If expensive, delay until needed and then don’t do it again
public class Foo {
    private static final Foo instance = new Foo();
    // private constructor prevents instantiation outside class
    private Foo() { ... }
    public static Foo getInstance() {
        return instance;
    }
    ... instance methods as usual ...
}

Eager allocation of instance

public class Foo {
    private static Foo instance;
    // private constructor prevents instantiation outside class
    private Foo() { ... }
    public static synchronized Foo getInstance() {
        if (instance == null) {
            instance = new Foo();
        }
        return instance;
    }
    ... instance methods as usual ...
}

Lazy allocation of instance

How: multiple approaches
GoF patterns: three categories

**Creational Patterns** are about the object-creation process
   Factory Method, Abstract Factory, *Singleton*, Builder, Prototype, …

**Structural Patterns** are about how objects/classes can be combined
   Adapter, Bridge, *Composite*, Decorator, Façade, Flyweight, Proxy, …

**Behavioral Patterns** are about communication among objects

Green = ones we’ve seen already
Creational patterns

Constructors in Java are inflexible

1. Can't return a subtype of the class they belong to
2. Always return a fresh new object, never re-use one

Factories: Patterns for code that you call to get new objects other than constructors

- Factory method, Factory object, Prototype, Dependency injection

Sharing: Patterns for reusing objects (to save space and other reasons)

- Singleton, Interning, Flyweight
Motivation for factories: Changing implementations

Supertypes support multiple implementations

```java
interface Matrix { ... }
class SparseMatrix implements Matrix { ... }
class DenseMatrix implements Matrix { ... }
```

Clients use the supertype (Matrix)

Still need to use a SparseMatrix or DenseMatrix constructor

- Must decide concrete implementation somewhere
- Don’t want to change code to use a different constructor
- Factory methods put this decision behind an abstraction
Use of factories

Factory

```java
class MatrixFactory {
    public static Matrix createMatrix() {
        return new SparseMatrix();
    }
}
```

Clients call `createMatrix` instead of a particular constructor

Advantages:
- To switch the implementation, change only one place
- `createMatrix` can do arbitrary computations to decide what kind of matrix to make (unlike what’s shown above)
**DateFormat factory methods**

`DateFormat` class encapsulates knowledge about how to format dates and times as text

- Options: just date? just time? date+time? where in the world?
- Instead of passing all options to constructor, use factories
- The subtype created by factory call need not be specified

```java
DateFormat df1 = DateFormat.getDateInstance();
DateFormat df2 = DateFormat.getTimeInstance();
DateFormat df3 = DateFormat.getDateInstance(DateFormat.FULL, Locale.FRANCE);

Date today = new Date();

df1.format(today) // "Jul 4, 1776"
df2.format(today) // "10:15:00 AM"
df3.format(today); // "jeudi 4 juillet 1776"
```
Example: Bicycle race

class Race {
    public Race() {
        Bicycle bike1 = new Bicycle();
        Bicycle bike2 = new Bicycle();
        ...
    }
    ...
}

New example:

• No factories yet
• Coming: factories for the bicycles to get flexibility and code reuse
• Could also use factories for the races, but that complicates the example, so will stick with constructors
class TourDeFrance extends Race {
    public TourDeFrance() {
        Bicycle bike1 = new RoadBicycle();
        Bicycle bike2 = new RoadBicycle();
        ...
    }
    ...
}

The problem: We are reimplementing the constructor in every Race subclass just to use a different subclass of Bicycle
class Cyclocross extends Race {
    public Cyclocross() {
        Bicycle bike1 = new MountainBicycle();
        Bicycle bike2 = new MountainBicycle();
        ...
    }
    ...
}

The problem: We are reimplementing the constructor in every Race subclass just to use a different subclass of Bicycle
Factory *method* for Bicycle

```java
class Race {
    Bicycle createBicycle() { return new Bicycle(); }
    public Race() {
        Bicycle bike1 = createBicycle();
        Bicycle bike2 = createBicycle();
        ...
    }
}
```

Use a factory method to avoid dependence on specific new kind of bicycle in the constructor

- Call the factory method instead
Subclasses override factory method

```java
class TourDeFrance extends Race {
    Bicycle createBicycle() {
        return new RoadBicycle();
    }
    public TourDeFrance() { super(); }
}
class Cyclocross extends Race {
    Bicycle createBicycle() {
        return new MountainBicycle();
    }
    public Cyclocross() { super(); }
}
```

- “Foresight” to use factory method in superclass constructor
- Then dynamic dispatch to call overridden method
- Subtyping in the overriding methods (covariant returns type also ok)
- Would look like even more code reuse outside of constructors
  - Example: Can inherit an `addBicycle` that calls `createBicycle`
Next step

• `createBicycle` was just a factory method

• Now let’s move the method into a separate class
  – So it’s part of a *factory object*

• Advantages:
  1. Can group related factory methods together
     • Not shown: `repairBicycle`, `createSpareWheel`, …
  2. Can pass factories around as objects for flexibility
     • Choose a factory at runtime
     • Use different factories in different objects (e.g., races)
     • Example…
Factory objects/classes encapsulate factory method(s)

class BicycleFactory {
    Bicycle createBicycle() {
        return new Bicycle();
    }
}
class RoadBicycleFactory extends BicycleFactory {
    Bicycle createBicycle() {
        return new RoadBicycle();
    }
}
class MountainBicycleFactory extends BicycleFactory {
    Bicycle createBicycle() {
        return new MountainBicycle();
    }
}
Using a factory object

class Race {
    BicycleFactory bfactory;
    public Race(BicycleFactory f) {
        bfactory = f;
        Bicycle bike1 = bfactory.createBicycle();
        Bicycle bike2 = bfactory.createBicycle();
        ...
    }
    public Race() { this(new BicycleFactory()); }    
    ...
}

Setting up the flexibility here:
  • Factory object stored in a field, set by constructor
  • Can take the factory as a constructor-argument
  • But an implementation detail (?), so 0-argument constructor too
    – Java detail: call another constructor in same class with this
The subclasses

class **TourDeFrance** extends Race {
   public TourDeFrance() {
      super(new RoadBicycleFactory());
   }
}

class **Cyclocross** extends Race {
   public Cyclocross() {
      super(new MountainBicycleFactory());
   }
}

Voila!

- Just call the superclass constructor with a different factory
- **Race** class had foresight to delegate “what to do to create a bicycle” to the factory object, making it more reusable
Separate control over bicycles and races

class TourDeFrance extends Race {
    public TourDeFrance() {
        super(new RoadBicycleFactory()); // or this(...)
    }
    public TourDeFrance(BicycleFactory f) {
        super(f);
    }
    ...
}

By having factory-as-argument option, we can allow arbitrary mixing by client: new TourDeFrance(new TricycleFactory())

Less useful in this example (?): Swapping in different factory object whenever you want

Reminder: Not shown here is also using factories for creating races
Prototype pattern

• Every object is itself a factory
• Each class contains a clone method that creates a copy of the receiver object

```java
class Bicycle {
    Bicycle clone() { ... }
}
```

Often, Object is the return type of clone
  – clone is declared in Object
  – Design flaw in Java 1.4 and earlier: the return type may not change covariantly in an overridden method
    i.e., return type could not be made more restrictive
Using prototypes

class Race {
    Bicycle bproto;

    public Race(Bicycle bproto) {
        this.bproto = bproto;
        Bicycle bike1 = (Bicycle) bproto.clone();
        Bicycle bike2 = (Bicycle) bproto.clone();
        ...
    }
}

Again, we can specify the race and the bicycle separately:
new Race(new Tricycle())
Dependency injection

• Change the factory without changing the code
• With a regular in-code factory:
  
  \[
  \text{BicycleFactory } f = \text{new TricycleFactory}();
  \]
  \[
  \text{Race } r = \text{new TourDeFrance}(f)
  \]
• With external dependency injection:
  
  \[
  \text{BicycleFactory } f = ((\text{BicycleFactory})
  \text{DependencyManager.get("BicycleFactory")});
  \]
  \[
  \text{Race } r = \text{new TourDeFrance}(f);
  \]
• \textit{Plus} an external file:
  
  \[
  <\text{service-point id="BicycleFactory"}>
  <\text{invoke-factory}>
  <\text{construct class="Bicycle"}>
  <\text{service}>Tricycle</service>
  </\text{construct}>
  </\text{invoke-factory}>
  </\text{service-point}>
  \]

  + Change the factory without recompiling
  - External file is essential part of program
Factories: summary

Problem: want more flexible abstractions for what class to instantiate

Factory method
- Call a method to create the object
- Method can do any computation and return any subtype

Factory object
- Bundles factory methods for a family of types
- Can store object in fields, pass to constructors, etc.

Prototype
- Every object is a factory, can create more objects like itself
- Call \texttt{clone} to get a new object of same subtype as receiver

Dependency Injection
- Put choice of subclass in a file to avoid source-code changes or even recompiling when decision changes
Sharing

Recall the second weakness of Java constructors
Java constructors always return a *new object*

**Singleton:** only one object exists at runtime
- Factory method returns the same object every time
- (we’ve seen this already)

**Interning:** only one object with a particular (abstract) value exists at runtime
- Factory method returns an existing object, not a new one

**Flyweight:** separate intrinsic and extrinsic state, represent them separately, and intern the intrinsic state
Interning pattern

- Reuse existing objects instead of creating new ones
  - Less space
  - May compare with `==` instead of `equals()`
- Sensible only for immutable objects

StreetSegment without string interning

StreetSegment with string interning
**Interning mechanism**

- Maintain a collection of all objects
- If an object already appears, return that instead

```java
HashMap<String, String> segnames;
String canonicalName(String n) {
    if (segnames.containsKey(n)) {
        return segnames.get(n);
    } else {
        segnames.put(n, n);
        return n;
    }
}
```

- Java builds this in for strings: `String.intern()`
- Two approaches:
  - Create the object, but perhaps discard it and return another
  - Check against the arguments before creating the new object

Why not `Set<String>`?
Set supports `contains` but not `get`
Space leaks

• Interning can waste space if your collection:
  – Grows too big
  – With objects that will never be used again

• Not discussed here: The solution is to use weak references
  – This is their canonical purpose

• Do not reinvent your own way of keeping track of whether an object in the collection is being used
  – Too error-prone
  – Gives up key benefits of garbage-collection
java.lang.Boolean
does not use the Interning pattern

```java
public class Boolean {
    private final boolean value;
    // construct a new Boolean value
    public Boolean(boolean value) {
        this.value = value;
    }

    public static Boolean FALSE = new Boolean(false);
    public static Boolean TRUE = new Boolean(true);

    // factory method that uses interning
    public static Boolean valueOf(boolean value) {
        if (value) {
            return TRUE;
        } else {
            return FALSE;
        }
    }
}
```
Recognition of the problem

Javadoc for Boolean constructor:
Allocates a Boolean object representing the value argument.

Note: It is rarely appropriate to use this constructor. Unless a new instance is required, the static factory valueOf(boolean) is generally a better choice. It is likely to yield significantly better space and time performance.

Josh Bloch (JavaWorld, January 4, 2004):
The Boolean type should not have had public constructors. There's really no great advantage to allow multiple trues or multiple falses, and I've seen programs that produce millions of trues and millions of falses, creating needless work for the garbage collector.
So, in the case of immutables, I think factory methods are great.
Flyweight pattern

Good when many objects are mostly the same
  – Interning works only if objects are entirely the same (and immutable)

Intrinsic state: Independent of object’s “context”
  – Often same across many objects and immutable
  – Technique: intern it

Extrinsic state: different for different objects; depends on “context”
  – Have clients store it separately, or better:
    – Advanced technique:
      • Make it implicit (clients compute it instead of represent it)
      • Saves space
Example without flyweight: bicycle spoke

```java
class Wheel {
    FullSpoke[] spokes;
    ...
}

class FullSpoke {
    int length;
    int diameter;
    boolean tapered;
    Metal material;
    float weight;
    float threading;
    boolean crimped;
    int location; // position on the rim
}
```

- Typically 32 or 36 spokes per wheel but only 3 varieties per bicycle
- In a bike race, hundreds of spoke varieties, millions of instances
Alternatives to FullSpoke

```java
class IntrinsicSpoke {
    int length;
    int diameter;
    boolean tapered;
    Metal material;
    float weight;
    float threading;
    boolean crimped;
}
```

This does not save space compared to FullSpoke

```java
class InstalledSpokeFull extends IntrinsicSpoke {
    int location;
}
```

This does saves space

```java
class InstalledSpokeWrapper {
    IntrinsicSpoke s; // refer to interned object
    int location;
}
```

But flyweight version [still coming up] uses even less space…
class FullSpoke {
    // Tension the spoke by turning the nipple the
    // specified number of turns.
    void tighten(int turns) {
        ... location ...  // location is a field
    }
}

class Wheel {
    FullSpoke[] spokes;
    void align() {
        while (wheel is misaligned) {
            // tension the i\textsuperscript{th} spoke
            ... spokes[i].tighten(numturns) ...
        }
    }
}

What is the value of the `location` field in `spokes[i]`?
Flyweight code to true (align) a wheel

class IntrinsicSpoke {
    void tighten(int turns, int location) {
        ... location ...  // location is a parameter
    }
}

class Wheel {
    IntrinsicSpoke[] spokes;

    void align() {
        while (wheel is misaligned) {
            // tension the ith spoke
            ... spokes[i].tighten(numturns, i) ...
        }
    }
}
What happened

• *Logically*, each spoke is a different object
  – A spoke “has” all the intrinsic state and a location

• But if that would be a lot of objects, i.e., space usage, we can instead…

• Create *one actual* flyweight object that is used “in place of” all logical objects that have that intrinsic state
  – Use interning to get the sharing
  – Clients store or compute the extrinsic state and pass it to methods to get the right behavior
  – Only do this when logical approach is cost-prohibitive and it’s not too complicated to manage the extrinsic state
    • Here spoke location was particularly easy and cheap because it was implicit in array location of reference
Flyweight discussion

What if FullSpoke contains a wheel field pointing at the Wheel containing it?

Wheel methods pass this to the methods that use the wheel field.

What if FullSpoke contains a boolean field broken?

Add an array of booleans in Wheel, parallel to the array of Spokes.
Flyweight: resist it

- Flyweight is manageable only if there are very few mutable (extrinsic) fields
- Flyweight complicates the code
- Use flyweight only when profiling has determined that space is a serious problem