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)
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
  - \texttt{List<Date>} instead of just \texttt{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
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
How: multiple approaches

```java
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 ...
}
```

```java
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 ...
}
```

Eager allocation of instance

Lazy allocation of instance
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

```
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));  // "jueudi 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
Example: Tour de France

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
Example: Cyclocross

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:

```java
BicycleFactory f = new TricycleFactory();
Race r = new TourDeFrance(f)
```

• With external dependency injection:

```java
BicycleFactory f = ((BicycleFactory)
DependencyManager.get("BicycleFactory"));
Race r = new TourDeFrance(f);
```

• *Plus* an external file:

```xml
<service-point id="BicycleFactory">
  <invoke-factory>
    <construct class="Bicycle">
      <service>Tricycle</service>
    </construct>
  </invoke-factory>
</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 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 \textit{new object}

\textbf{Singleton}: only one object exists at runtime
\begin{itemize}
  \item Factory method returns the same object every time
  \item (we’ve seen this already)
\end{itemize}

\textbf{Interning}: only one object with a particular (abstract) value exists at runtime
\begin{itemize}
  \item Factory method returns an existing object, not a new one
\end{itemize}

\textbf{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
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
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 true\text{\_}s or multiple false\text{\_}s, and I've seen programs that produce millions of true\text{\_}s and millions of false\text{\_}s, 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

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

This does saves space
```
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

```java
class IntrinsicSpoke {
    void tighten(int turns, int 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