CSE 331
Software Design & Implementation

Hal Perkins
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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)

Future lectures:

• 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
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
class Race {

    // factory method for bicycle race
    Race createRace() {
        Bicycle bike1 = new Bicycle();
        Bicycle bike2 = new Bicycle();
        ...
    }

}
Example: Tour de France

class TourDeFrance extends Race {

    // factory method
    Race createRace() {
        Bicycle bike1 = new RoadBicycle();
        Bicycle bike2 = new RoadBicycle();
        ...
    }
}

The problem: We are reimplementing createRace in every Race subclass just to use a different subclass of Bicycle.
Example: Cyclocross

class Cyclocross extends Race {

    // factory method
    Race createRace() {
        Bicycle bike1 = new MountainBicycle();
        Bicycle bike2 = new MountainBicycle();
        ...
    }

}

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

```java
class Race {
    Bicycle createBicycle() { ... }
    Race createRace() {
        Bicycle bike1 = createBicycle();
        Bicycle bike2 = createBicycle();
        ...
    }
}
```

Use a factory method to avoid dependence on specific new kind of bicycle in `createRace`  
- Now the Race factory calls the Bicycle factory
Code using Bicycle factory methods

class Race {
    Bicycle createBicycle() {
        return new Bicycle();
    }
    Race createRace() {
        Bicycle bike1 = createBicycle();
        Bicycle bike2 = createBicycle();
        ...
    }
}

class TourDeFrance extends Race {
    Bicycle createBicycle() {
        return new RoadBicycle();
    }
}

class Cyclocross extends Race {
    Bicycle createBicycle() {
        return new MountainBicycle();
    }
}
Factory objects/classes encapsulate factory methods

class BicycleFactory {
    Bicycle createBicycle() { ... }
    Frame createFrame() { ... }
    Wheel createWheel() { ... }
    ...
}
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;
    Race() { bfactory = new BicycleFactory(); }
    Race createRace() {
        Bicycle bike1 = bfactory.createBicycle();
        Bicycle bike2 = bfactory.createBicycle();
        ...
    }
}

class TourDeFrance extends Race {
    TourDeFrance() {
        bfactory = new RoadBicycleFactory();
    }
}

class Cyclocross extends Race {
    Cyclocross() {
        bfactory = new MountainBicycleFactory();
    }
}
Separate control over bicycles and races

class Race {
    BicycleFactory bfactory;
    // constructor
    Race(BicycleFactory bfactory) {
        this.bfactory = bfactory;
    }
    Race createRace() {
        Bicycle bike1 = bfactory.completeBicycle();
        Bicycle bike2 = bfactory.completeBicycle();
        ...
    }
}
// No difference in constructors for
// TourDeFrance or Cyclocross (just give
// BicycleFactory to super constructor)

Now we can specify the race and the bicycle separately:
    new TourDeFrance(new TricycleFactory())
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));// "jueudi 4 juillet 1776"
```
Prototype pattern

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

```
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;
    // constructor
    Race(Bicycle bproto) { this.bproto = bproto; }
    Race createRace() {
        Bicycle bike1 = (Bicycle) bproto.clone();
        Bicycle bike2 = (Bicycle) bproto.clone();
        ...
    }
}

Again, we can specify the race and the bicycle separately:

    new TourDeFrance(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:
  \[
  \begin{align*}
  &\text{<service-point id="BicycleFactory">} \\
  &\text{<invoke-factor}> \\
  &\text{<construct class="Bicycle">} \\
  &\text{<service>Tricycle</service>} \\
  &\text{</construct>} \\
  &\text{</invoke-factor>} \\
  &\text{</service-point>}
  \end{align*}
  \]

+ 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 objects 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 (we’ve seen this already)
   \end{itemize}

\textbf{Interner}: 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

StreetSegment without string interning

StreetSegment with string interning
Interner 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

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 save 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

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