

Java reflection, proxies, and annotations

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Motivation

- Annotations and reflection is widely used in frameworks
- Microservice, dependency injection, persistence frameworks



Java annotations preview

- Annotations are “metadata” added to Java code
- By themselves, they have no direct impact on code execution at runtime
- Java provides some annotations, programmer can define more
- Syntax: `@Annotation_name`

```
@Annotation1
public class Car {
    @Annotation2
    private int speed;

    public Car(int speed) {
        this.speed = speed;
    }

    @Annotation3
    public void accelerate(int moreSpeed) {
        this.speed += moreSpeed;
    }

    @Annotation3
    public void decelerate(int lessSpeed) {
        this.speed -= lessSpeed;
    }
}
```

Annotation targets

- Annotations can be applied to
 - Classes
 - Fields
 - Methods
 - ... many other program elements (Check <https://docs.oracle.com/javase/tutorial/java/annotations/basics.html>)

Motivation: Junit

```
public class Car {
    private String model;
    private int speed;

    public Car(String model, int speed) {
        this.model = model;
        this.speed = speed;
    }

    public int getSpeed() { return speed; }
    public String getModel() { return model; }

    ... // setters

    public void accelerate() {
        this.speed += 10;
    }
}
```

```
import org.junit.jupiter.api.Test;
import
org.junit.jupiter.api.Assertions.assertEquals;
```

```
public class CarTest {
    @Test
    public void testAccelerate() {
        Car car = new Car("Toyota", 50);
        car.accelerate();
        assertEquals(car.getSpeed(), 60);
    }
}
```

```
[INFO] -----
[INFO] T E S T S
[INFO] -----
[INFO] Running CalculatorTest
[INFO] Tests run: 2, Failures: 0, Errors: 0, Skipped: 0, Time elapsed: 0.068 s - in CalculatorTest
[INFO] Results:
[INFO]
[INFO] Tests run: 2, Failures: 0, Errors: 0, Skipped: 0
[INFO] -----
[INFO] BUILD SUCCESS
[INFO] -----
[INFO] Total time: 4.399 s
[INFO] Finished at: 2024-10-02T20:46:10+05:30
[INFO] -----
PS C:\Users\Syam\OneDrive\Desktop\Spring Projects\JUnitMavenExample>
```


Motivation: Hibernate

- Automatically load and store Java objects from a SQL database

users

id	name

```
@Entity
@Table(name = "users")
public class User {

    @Id
    private Long id;

    private String name;

    protected User() {} // required by Hibernate

    public User(String name) {
        this.name = name;
    }

    public Long getId() { return id; }
    public String getName() { return name; }
}

public static void main(String[] args) {
    SessionFactory factory = ...;
    Session session = factory.openSession();

    User u = new User("Alice");
    session.persist(u);
}
```

Motivation: Hibernate

Hibernate annotations

- Automatically load and store Java objects from a SQL database

users

id	name

```
@Entity
@Table(name = "users")
public class User {

    @Id
    private Long id;

    private String name;

    protected User() {} // required by Hibernate

    public User(String name) {
        this.name = name;
    }

    public Long getId() { return id; }
    public String getName() { return name; }
}
```

Hibernate classes

```
public static void main(String[] args) {
    SessionFactory factory = ...;
    Session session = factory.openSession();

    User u = new User("Alice");
    session.persist(u);
}
```

Motivation: Hibernate

- Automatically load and store Java objects from a SQL database

users

id	name
102811	Alice

```
@Entity
@Table(name = "users")
public class User {

    @Id
    private Long id;

    private String name;

    protected User() {} // required by Hibernate

    public User(String name) {
        this.name = name;
    }

    public Long getId() { return id; }
    public String getName() { return name; }
}

public static void main(String[] args) {
    SessionFactory factory = ...;
    Session session = factory.openSession();

    User u = new User("Alice");
    session.persist(u);
}
```


Reflection and metaprogramming

- Ability of a program to inspect and manipulate its own structure and behavior at runtime **within the same language environment**
- Can (dynamically) instantiate classes given a **class name** and invoke methods and constructors on it
- Types of Reflection
 - Run time (now)
 - Compile time (later)
- Supported by Java, Go, Javascript

Java reflection

- Provides APIs to inspect and manipulate the classes, methods, fields, and so on...
- Note: reflection bypasses all encapsulation guarantees
 - You can directly access private class fields and methods from outside the class using reflection
 - But (hopefully) for greater good!!

Key classes

- `java.lang.Class`: Represents metadata for a class or interface
- `java.lang.reflect.Method`: Represents metadata for a class method
- `java.lang.reflect.Field`: Represents metadata for a class field
- `java.lang.reflect.Constructor`: Represents metadata for a constructor
- Automatically defined by the Java runtime

public class Student

```
private int id;
```

```
private String name;
```

```
public void setId(..) {..}
```

```
//... other getters and  
setters
```

public class Class

```
private String className;
```

```
private Class<?>[] classes;
```

```
private Constructor<?>[] constructors;
```

```
private Field[] fields;
```

```
private Method[] methods;
```

```
// getters, setters, other methods
```

public class Method

```
// ... meta-info
```

public class Field

```
// ... meta-info
```

public class Constructor

```
// ... meta-info
```

Key classes

- Java runtime also automatically creates a `Class` object for every class you define
- Contains objects of type `Method`, `Field`, etc

public class Student

```
private int id;  
private String name;  
public void setId(..) {..  
//... other getters and  
setters
```

public class Class

```
private String className;  
private Class<?>[] classes;  
private Constructor<?>[] constructors;  
private Field[] fields;  
private Method[] methods;  
// getters, setters, other methods
```

Class studentClass\$1 /* object of type Class */

```
className = "Student";  
classes = [];  
constructors = defCons$1;  
fields = [field$1, field$2];  
methods = [method$1, method$2];
```

Key classes

- Java runtime also automatically creates a Class object for every class you define
- Contains objects of type Method, Field, etc

public class Student

```
private int id;
```

```
private String name;
```

```
public void setId(..) {..}
```

```
//... other getters and  
setters
```

public class Method

```
private String methodName;
```

```
private Type[] argTypes;
```

```
private Type returnType;
```

```
// getters, setters, other methods
```

Method method\$1 /* object of type Method */

```
methodName = "setId";
```

```
argTypes = [IntegerType];
```

```
returnType = VoidType;
```


Key classes

- Java runtime also automatically creates a Class object for every class you define
- Contains objects of type Method, Field, etc

public class Student

```
private int id;
```

```
private String name;
```

```
public void setId(..) {..}
```

```
//... other getters and  
setters
```

public class Field

```
private String fieldName;
```

```
private Type[] fieldType
```

```
// getters, setters, other methods
```

Field Field\$1 /* object of type Field */

```
fieldName = "Id";
```

```
fieldType = IntegerType;
```

```
//..
```

Key classes

- The programmer can manipulate these reflection objects (Class, Field, Method, etc)

Class studentClass\$1 /* object of type Class */

className = "Student";

classes = [];

constructors = defCons\$1;

fields = [field\$1, field\$2];

methods = [method\$1, method\$2];

public class Student

private int id;

private String name;

public void setId() {..}

//... other getters and
setters

Method method\$1 /* object of type Method */

methodName = "setId";

argTypes = [IntegerType];

returnType = VoidType;

Field Field\$1 /* object of type Field */

fieldName = "Id";

fieldType = IntegerType;

//..

Key classes

- Reflection objects independent of class objects

Class studentClass\$1 /* object of type Class */

className = "Student";

classes = [];

constructors = defCons\$1;

fields = [field\$1, field\$2];

methods = [method\$1, method\$2];

public class Student

private int id;

private String name;

public void setId() {..}

//... other getters and
setters

Student studentObj1

101

Student studentObj2

102

"DEF"

Method method\$1 /* object of type Method */

methodName = "setId";

argTypes = [IntegerType];

returnType = VoidType;

Field Field\$1 /* object of type Field */

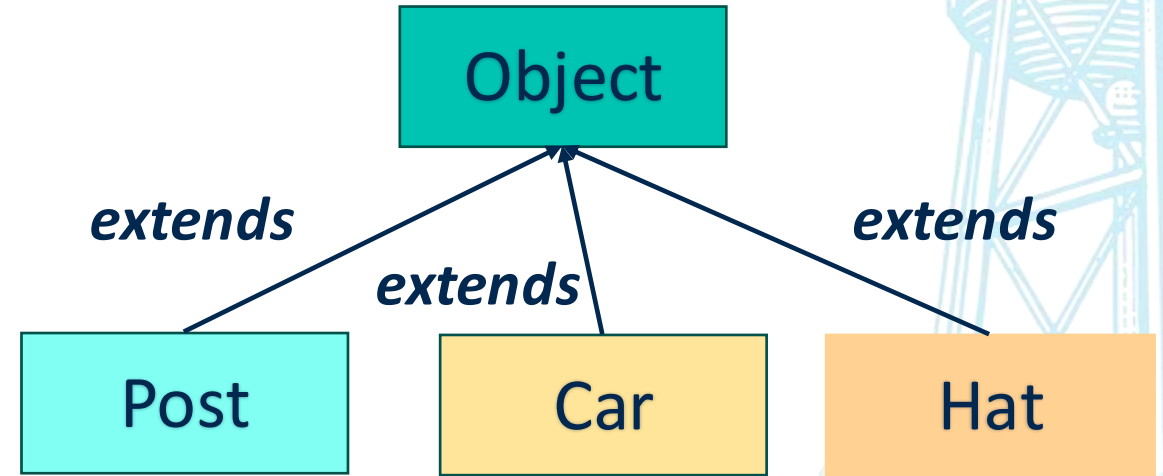
fieldName = "Id";

fieldType = IntegerType;

//..

Background

- In Java, all classes inherit the Object class implicitly



Reflection API

- `java.lang.reflect.Class`
 - An object of this type encapsulates the class metadata for a particular class
 - `Class clazz = Class.forName("com.ecs160.MyApp");`
 - `Class clazz = obj.getClass();`
- `clazz.getMethods()`: Get an array of methods of class `clazz`
- `java.lang.reflect.Method`
 - Invoke using `m.invoke(obj, [args]);`
- `java.lang.reflect.Field`
 - Can get and set field values using `f.getValue(obj)`, `f.setValue(obj, val)`
 - Reflection can bypass access modifiers using the `setAccessible(true)` method
- Invoke constructor to create a new Object
 - `Object o = c.getConstructor().newInstance();`



Reflection API

- `java.lang.reflect.Class`
 - An object of this type encapsulates the class metadata for a particular class
 - `Class clazz = Class.forName("com.ecs160.MyApp");`

• `Class clazz = obj.getClass();`

```
public class Student
```

```
private int id;
```

```
private String name;
```

```
public void setId() {..}
```

```
//... other getters and  
setters
```

```
Student studentObj2
```

```
102
```

```
"DEF"
```

```
studentObj2.getClass()
```

```
Class studentClass$1 /* object of type Class */
```

```
className = "Student";
```

```
classes = [];
```

```
constructors = defCons$1;
```

```
fields = [field$1, field$2];
```

```
methods = [method$1, method$2];
```

Reflection API

- `clazz.getMethods()`: Get an array of methods of class `clazz`

- `java.lang.reflect.Method`
- Invoke using `m.invoke(obj, [args]);`

```
Class studentClass$1 /* object of type Class */
```

```
className = "Student"; studentClass$1.getMethods()
```

```
classes = [];
```

```
constructors = defCons$1;
```

```
fields = [field$1, field$2];
```

```
methods = [method$1, method$2];
```

```
public class Student
```

```
private int id;
```

```
private String name;
```

```
public void setId() {..}
```

```
//... other getters and  
setters
```

```
Student studentObj2
```

```
102
```

```
"DEF"
```

```
studentObj2.getClass()
```

```
Method method$1 /* object of type Method */
```

```
methodName = "setId";
```

```
argTypes = [IntegerType];
```

```
returnType = VoidType;
```

```
method$1.invoke(studentObj2, 10);
```

```
==
```

```
studentObj2.setId(10);
```

Reflection example

- E.g., using reflection to dynamically invoke all methods in an object

```
class Car {
    private String model;
    private int year;
    public String getModel() {return model;}
    public int getYear() { return year; }
    public Car(String model, int year) {...}
}

class MyApp {
    public static void main(String[] args) {
        Car c = new Car("Toyota", 2019);
        Class<?> clazz = c.getClass();
        for (Method m: clazz.getDeclaredMethods()) {
            Object result = m.invoke(c);
            S.o.p(result);
        }
    }
}
// Prints "Toyota" and then "2019"
```

Same reflection code works on all objects

- Using reflection on another object type
- Allows the programmer to define functionality that works on objects of *any* class
- Demo:
https://github.com/davsec-teaching/reflection_demo/tree/master

```
class Post {
    private String authorName;
    private String content;
    private int replyCount;
    public int getAuthorName() { return authorName; }
    public int getContent() { return content; }
    public Integer getReplyCount() { return replyCount; }
    public Post(String authorName, String content,
        int replyCount) {
        this.authorName = authorName;
        this.content = content;
        this.replyCount = replyCount;
    }
}

class MyApp {
    public static void main(String[] args) {
        Post p = new Post("Tapti", "Welcome to ECS 160",
0);

        Class<?> clazz = p.getClass();
        for (Method m: clazz.getDeclaredMethods()) {
            Object result = m.invoke(p);
            S.o.p(result);
        }
    }
}
// Prints "Tapti" and then "Welcome to ECS 160" and then
"0"
```


Use case: Redis persistence framework

- Redis: REmote DIctionary Server
- In-memory data store
- Redis uses
 - As a temporary database
 - As a caching layer
 - As a message broker
- Goal: create a persistence framework for Redis that works with **any** objects

More in the Microservices module

Redis overview

- Redis is a key-value store
- Key: unique identifier for the record you're storing
- Value: String or collection of values of field-value pairs (hashmap)

Key	Value	
	Field	Value
10279811	Name	ABC
	Age	22
	GPA	3.8
	Credits	45
10279812	Name	DEF
	Age	21
	GPA	3.9
	Credits	60

Students

Jedis library

- Used to communicate with Redis server from local machine
- `String key = ... ;`
`String value = ...;`
`Jedis jedisSession = new Jedis("localhost", 6379);`
`jedisSession.set(key, value);`

Jedis library

```
Student s = new Student('ABC', 22, 3.8, 45);  
Jedis jedis = new Jedis("localhost", 6379);  
Map<String, String> studentMap = new HashMap<>();
```

```
studentMap.put("Name", s.getName());  
studentMap.put("Age", s.getAge());  
studentMap.put("GPA", s.getGPA());  
studentMap.put("Credits", s.getCredits());
```

```
jedis.hset("10279811", studentMap);
```

*Needs to be duplicated
for each class*

Why reflection?

- Goal: define persistAll method, independent of the object type

```
class Student { // fields of student}

class RedisDB {
    Jedis jedisSession;
    static int id;
    static {
        jedisSession = new Jedis("localhost", 6379);
        id = 0;
    }

    public void persistAll(Student s) {
        studentMap.put("Name", s.getName());
        studentMap.put("Age", s.getAge());
        studentMap.put("GPA", s.getGPA());
        studentMap.put("Credits", s.getCredits());
        jedis.hset(id++, studentMap);
    }
}
```

Solution: use reflection

```
class Student { // fields of student}

class RedisDB {
    Jedis jedisSession;
    static int id;
    static {
        jedisSession = new Jedis("localhost",
6379);
        id = 0;
    }

    public void persistAll(Student s) {
        studentMap.put("Name", s.getName());
        studentMap.put("Age", s.getAge());
        studentMap.put("GPA", s.getGPA());
        studentMap.put("Credits",
s.getCredits());
        jedis.hset(id++, studentMap);
    }
}
```

```
class Student {}
class Post { }
```

```
class RedisDB {
```

```
    public void persistAll(Object obj) {
        Map<String, String> objMap;
        Class c = obj.getClass();
        for (Field f: c.getDeclaredFields()) {
            String fieldname = f.getName();
            fieldVal.setAccessible(true);
            Object fieldVal = f.get(obj);
            objMap.put(fieldname, fieldVal);
        }
        jedis.hset(id++, objMap);
    }
}
```

```
}
```

```
Student s = new Student("ABC", ...);
Post p = new Post("Hello world", "1/23/2025");
RedisDB db = new RedisDB();
db.persistAll(s);
db.persistAll(p);
```


Loading all classes

- Can load all classes in application
- ```
ClassLoader cl = ClassLoader.getSystemClassLoader();
List<class> classes = cl.getClasses();
```

# Design problem: testing framework

- Design a framework that invokes all methods in all classes whose names start with Test
  - Assume all such methods do not have take any arguments
- ```
List<class> classes = classLoader.getClasses();  
for (Class clazz: classes) {  
    if (clazz.getName().startsWith("Test")) {  
        Object o = clazz.constructor.invoke();  
        for (Method m: clazz.getDeclaredMethods()) {  
            m.invoke(o);  
        }  
    }  
}
```

Drawback of previous approach

- All fields saved
- What if we want only a subset of all fields persisted?
- Solution: annotations

```
class Post { }

class RedisDB {
    Jedis jedisSession;
    static int id;
    static {
        jedisSession = new Jedis("localhost", 6379);
        id = 0;
    }

    public void persistAll(Object obj) {
        Map<String, String> postMap;
        for (Field f: obj.getDeclaredFields()) {
            String fieldname = f.getName();
            Object fieldVal = f.get(obj);
            fieldVal.setAccessible(true);
            postMap.put(fieldname, fieldVal.toString());
        }
        jedis.hset(id++, postMap);
    }
}

Post p = new Post("Hello world", "1/23/2025");
Car c = new Car("BMW");
RedisDB db = new RedisDB();
db.persistAll(p);
db.persistAll(c);
```

Java annotations

- Annotations are “metadata” added to Java code
- They have no direct impact on code execution at runtime
- Java provides some annotations, programmer can define more
- Syntax: `@Annotation_name`
- Widely used in popular frameworks

Annotation targets

- Annotations can be applied to
 - Classes
 - Fields
 - Methods
 - ... many other program elements (Check <https://docs.oracle.com/javase/tutorial/java/annotations/basics.html>)

Annotations for compiler checks

- Additional information for the compiler
 - Detect errors
 - Suppress warnings
- Common predefined annotations
 - `@Override`, `@Deprecated`, `@SuppressWarnings`

```
class Vehicle {  
    public void start() {  
        System.out.println("Vehicle starts");  
    }  
}  
  
class Bicycle extends Vehicle {  
    @Override  
    public void start() { ... }  
  
    @Override // COMPILER ERROR!  
    public void stop() { ... }  
}
```

Few common predefined annotations

- `@Override`
 - The annotated method must override a parent method. If not, results in compiler error
- `@Deprecated`
 - The annotated method is deprecated and will show a compiler warning if used
- `@SuppressWarnings`
 - Compiler errors for the annotated entity are suppressed

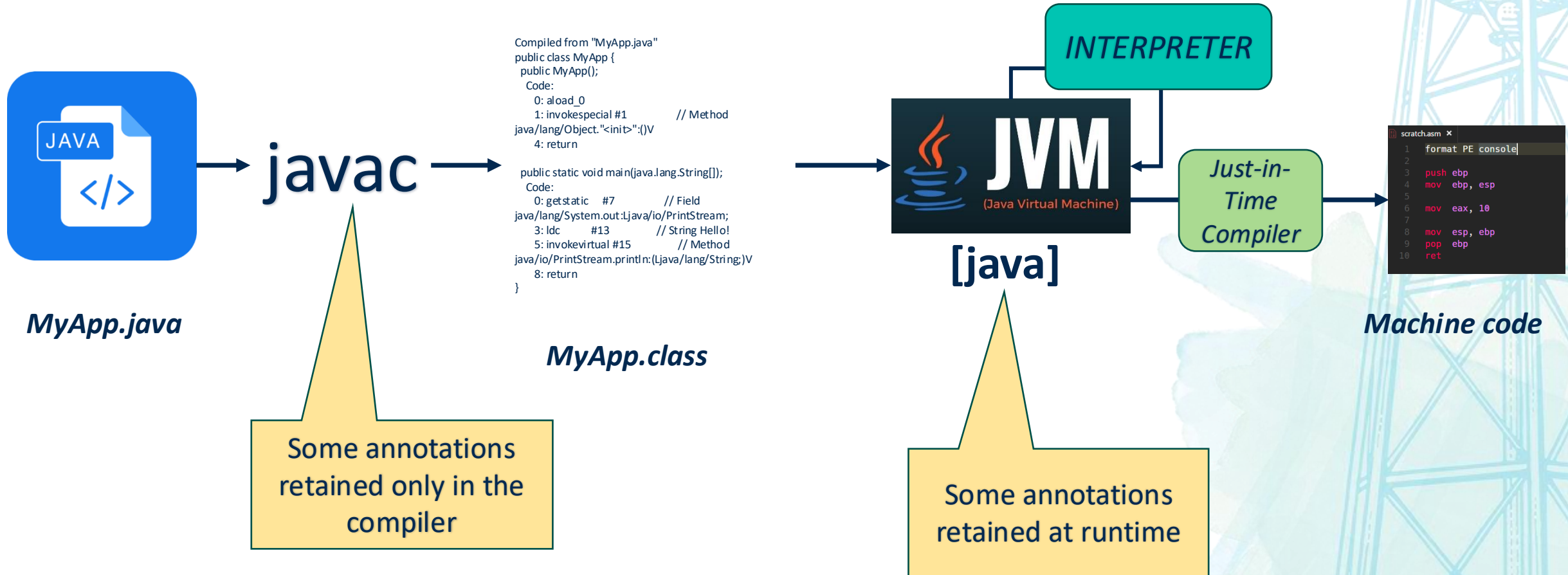
Defining new annotations

- Annotation definition must begin with `@interface`
- Annotations can have multiple fields
 - *Annotation type element* declarations
- Each field has a constructor
 - Constructors can have default values
- Fields can consist of arrays

```
@Retention(RetentionPolicy.RUNTIME)
@interface MyAnnotation {
    String author();
    String date();
    int currentRevision() default 1;
    String lastModified() default "N/A";
    String lastModifiedBy() default "N/A";
}
```

```
@MyAnnotation (
    author = "John Doe",
    date = "3/17/2002",
)
public class Car extends Vehicle {
    // ...
}
```

Recall: compilation toolchain



Reflection can access annotations

- Can check if annotation is present
 - `Class clazz = ... ;`
`clazz.isAnnotationPresent(MyAnnotation.class)`
 - `Field field = ...;`
`field.isAnnotationPresent(...);`
 - Same for Method
- Can get the annotation
 - `MyAnnotation myAnnotation = clazz.getAnnotation(MyAnnotation.class)`
- Can get the values of the annotation element fields

Drawback of previous approach

- All fields saved
- What if we want only a subset of all fields persisted?
- Solution: annotations

```
class Post { }

class RedisDB {
    Jedis jedisSession;
    static int id;
    static {
        jedisSession = new Jedis("localhost", 6379);
        id = 0;
    }

    public void persistAll(Object obj) {
        Map<String, String> postMap;
        Class c = obj.getClass();
        for (Field f: c.getDeclaredFields()) {
            String fieldname = f.getName();
            Object fieldVal = f.get(obj);
            objMap.put(fieldname, fieldVal);
        }
        jedis.hset(id++, objMap);
    }
}

Post p = new Post("Hello world", "1/23/2025");
Car c = new Car("BMV");
RedisDB db = new RedisDB();
db.persistAll(p);
db.persistAll(c);
```

Full solution

- Create an annotation
@Persistable with Runtime retention policy
- Annotate only some fields
- When persisting the fields, check if the annotation is present
- Only persist if the annotation is present

```
@Retention(RetentionPolicy.RUNTIME)
public @interface Persistable {
}
```

```
class Post {
    @Persistable
    private String content;
    private Integer tempVal;
}
```

```
class RedisDB {
    // ... set up Jedis Session
    public void persistAll(Object obj) {
        Map<String, String> objMap; Class c = obj.getClass();
        for (Field f: c.getDeclaredFields()) {
            if (f.isAnnotationPresent(Persistable.class) {
                f.setAccessible(true);
                String fieldname = f.getName();
                Object fieldVal = f.get(obj);
                objMap.put(fieldname, fieldVal);
            }
        }
        jedis.hset(id++, objMap);
    }
}
```

Annotations and retention policies

- The `@Retention` annotation indicates the retention policy for the annotation
- `@Retention(RetentionPolicy.SOURCE)` – only present in the source file
- `@Retention(RetentionPolicy.CLASS)` – only present in the class file
- `@Retention(RetentionPolicy.RUNTIME)` – present at runtime
- Reflection can only access annotations with `RetentionPolicy.RUNTIME`

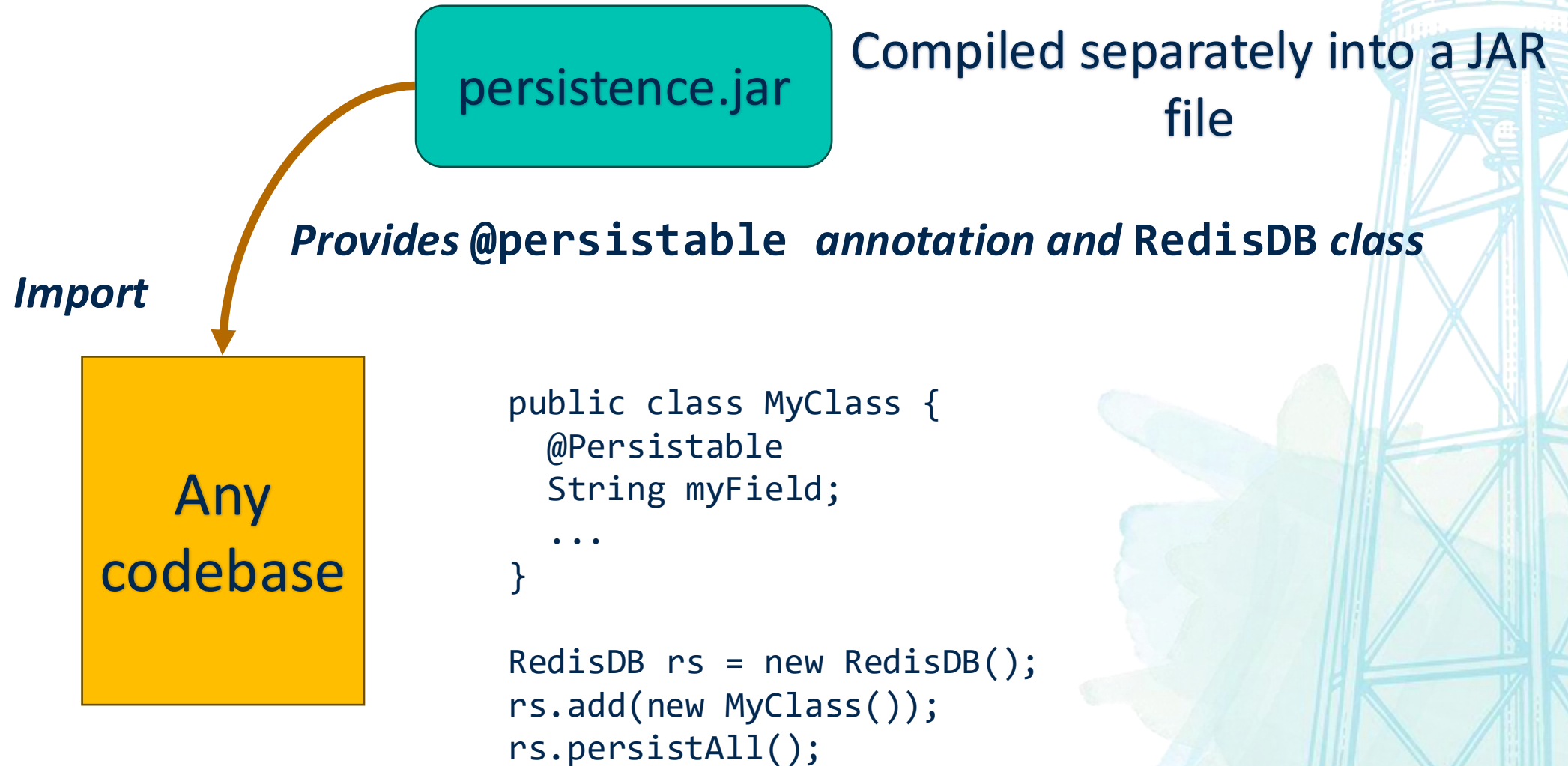
```
@Retention(RetentionPolicy.RUNTIME)
@interface MyAnnotation {
    String author();
    String date();
    int currentRevision() default 1;
    String lastModified() default "N/A";
    String lastModifiedBy() default "N/A";
}
```

Why would we want to create our own annotations visible only at the source code / class level?

Reflection + annotations: summary

- What did we achieve?
 - The ability to persist ***any*** object, provided it is annotated
 - The persistence framework ***does not need*** to know the classes that can be persisted
 - The persistence logic is ***fully decoupled*** from the application's data model

Distribute persistence framework as a library



Object relational mapping (ORM) frameworks

- Hibernate: allows the programmer to annotate a class with `@Entity`
- Provides an API `save()` that accepts an object of a class annotated with `@Entity` and saves it in the database
- The framework *abstracts* the SQL logic
- In-class demo



```
@Entity
public class Car {
    @Id
    @GeneratedValue(strategy= GenerationType.IDENTITY)
    private Long id;

    private String name;
    private String email;
}
```

Unit testing frameworks

- JUnit: allows the programmer to annotate a class with `@Test`
- Can specify pre- and post-operations
- All methods of the class automatically executed using Reflection
- The framework *abstracts* the invocation logic of the tests

JUnit 

```
public class CalculatorTest {  
    @Test  
    public void testAdd() {  
        calculator = new Calculator();  
        int result = calculator.add(2, 3);  
        assertEquals(5, result, "2 + 3 should equal 5");  
    }  
}
```

... and more

- Microservice frameworks
 - Spring Boot
- MVC frameworks
 - Spring MVC
- Logging frameworks
 - Log4j, SL4J
- ... and create other design patterns such as *Inversion of Control (IoC)*



LOG4J



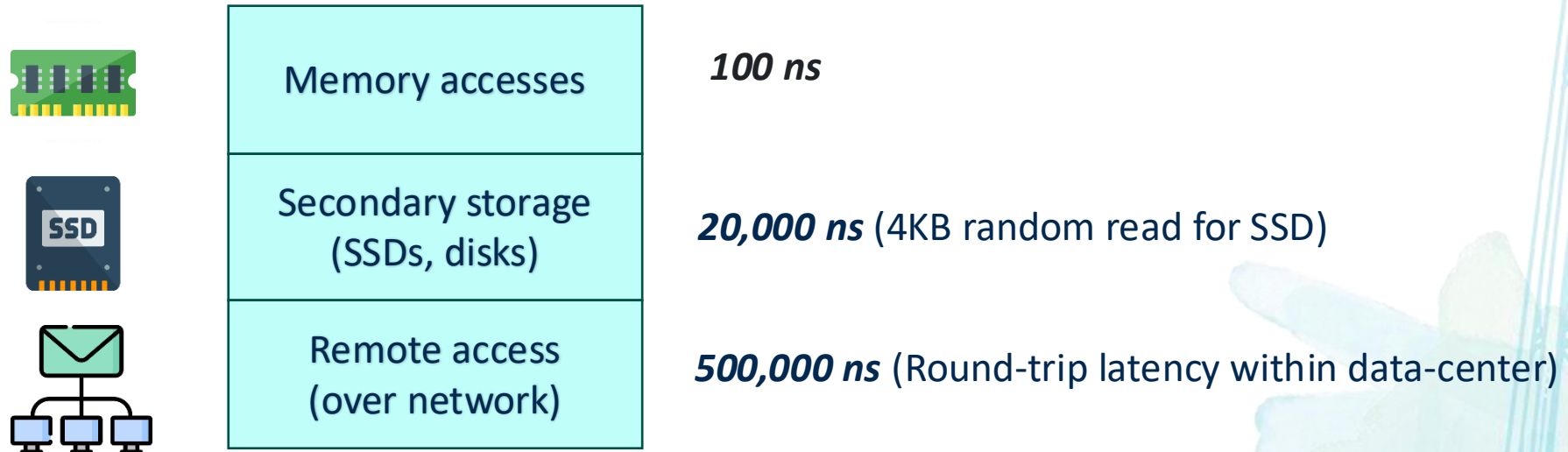
Downsides of reflection

- Cannot *generate* new methods, fields, etc.
- Reflection causes full loss of type safety
 - If you do `s.setName(new Integer(123));` compiler will catch it at compile time
 - If you do `setNameMethod.invoke(s, new Integer(123));` it will throw an exception at runtime
- Performance is slower than directly accessing the field/method
 - Needs more method calls and memory accesses to first load the field, then the value in the field
 - In some cases, it is okay
 - Database persistence, network communications
 - Why?

Latency hierarchy

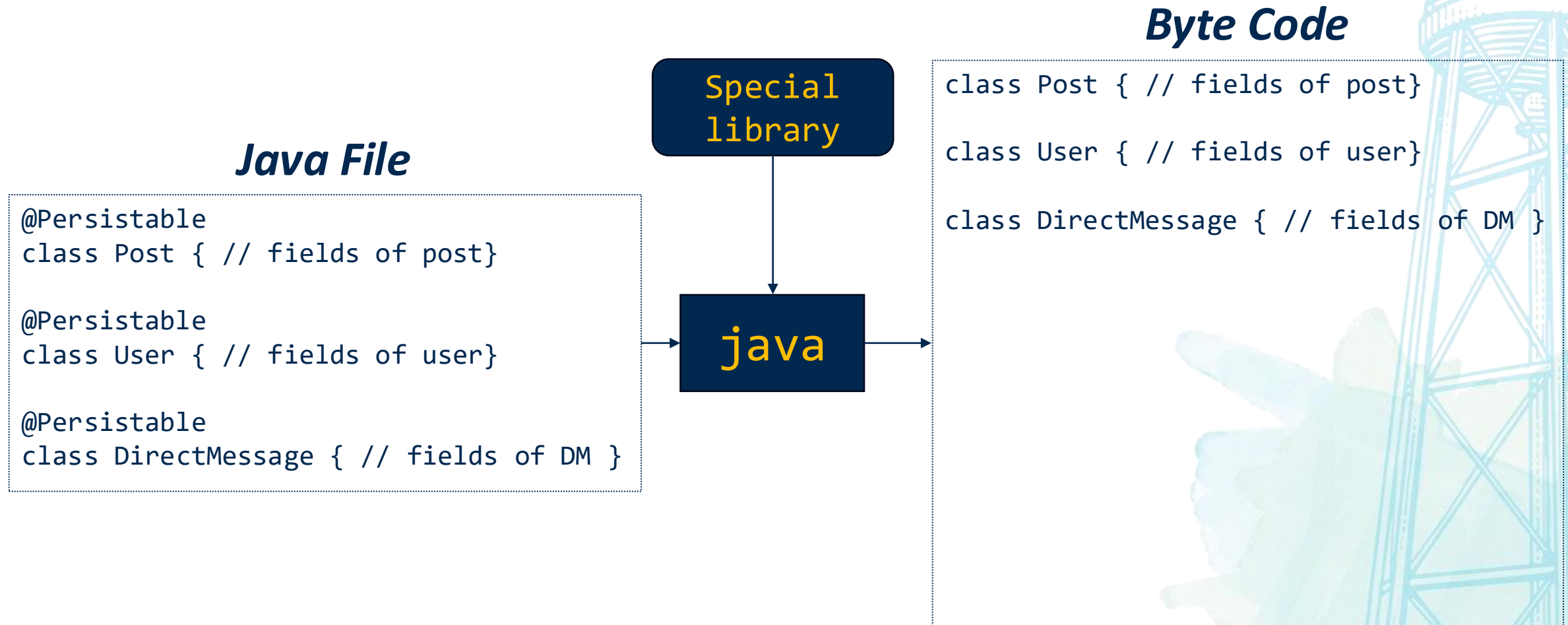
- CPU register << DRAM memory << SSDs << hard disks << network

<https://static.googleusercontent.com/media/sre.google/en//static/pdf/rule-of-thumb-latency-numbers-letter.pdf>

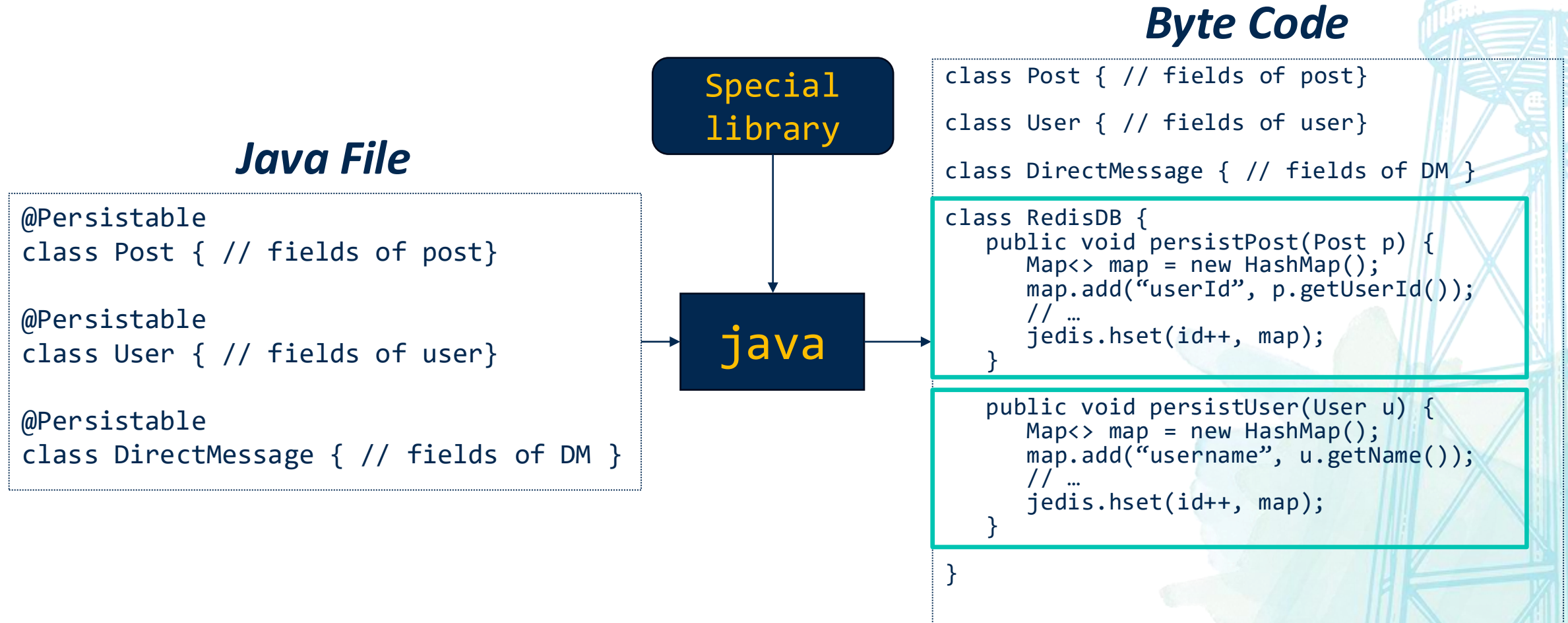


- Adding a few extra memory accesses for reflection is not noticeable for disk and network operations

Alternate approach: bytecode instrumentation



Alternate approach: bytecode instrumentation



Bytecode instrumentation

Java File

```
@Persistable
class Post { // fields of post}

@Persistable
class User { // fields of user}

@Persistable
class DirectMessage { // fields of DM }
```

Bytecode
instrumentation
libraries

java

Byte Code

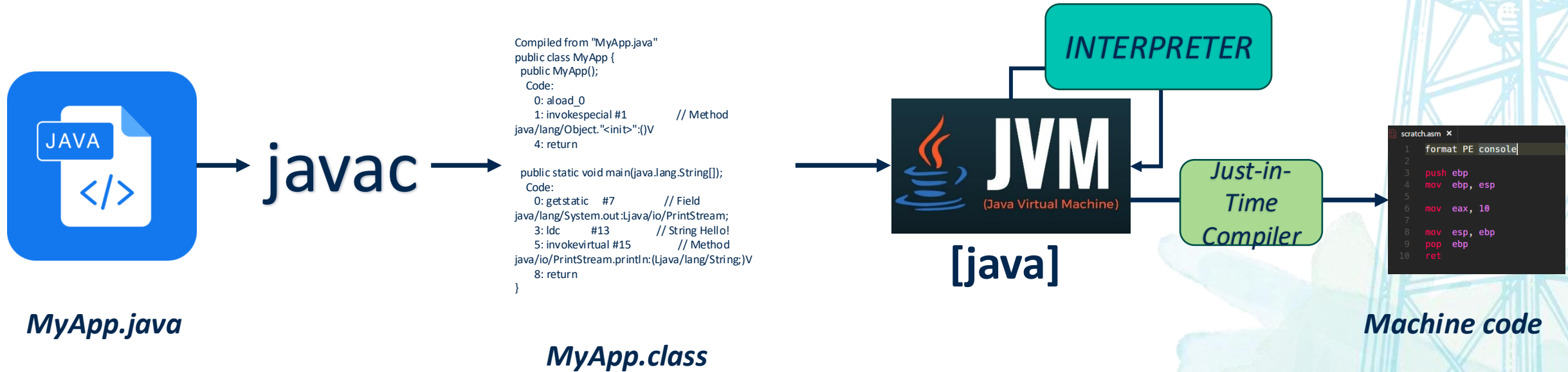
```
class Post { // fields of post}
class User { // fields of user}
class DirectMessage { // fields of DM }

class RedisDB {
    public void persistPost(Post p) {
        Map<> map = new HashMap();
        map.add("userId", p.getUserId());
        // ...
        jedis.hset(id++, map);
    }

    public void persistUser(User u) {
        Map<> map = new HashMap();
        map.add("username", u.getName());
        // ...
        jedis.hset(id++, map);
    }
}
```

Runtime bytecode generation and manipulation

- Recap what is bytecode?



- Bytecode is just a format!!

Runtime bytecode generation and manipulation



Used by Hibernate

Reflection in JavaScript [Not in Syllabus]

- Javascript Reflect API
- Reflect.get()
- Reflect.set()

```
const person = {  
  name: 'John Doe'  
};
```

```
const name = Reflect.get(person, 'name');  
console.log(name); // 'John Doe'
```

```
Reflect.set(person, 'name', 'Jane Doe');  
console.log(person.name); // 'Jane Doe'
```

Reflection in C++ [Not in Syllabus]

- RunTime Type Information (RTTI) maintains type information for each object
 - `Person person;`
`type_info personType = typeid(person);`
`std::println("{} ", personType.name());`
- But no language-level support for dynamic invocation
- Possible to programmatically enable support for dynamic invocation
- Describe with pseudo-code how you would design reflection for C++.
Assume that the programmer must manually enable reflection for a class

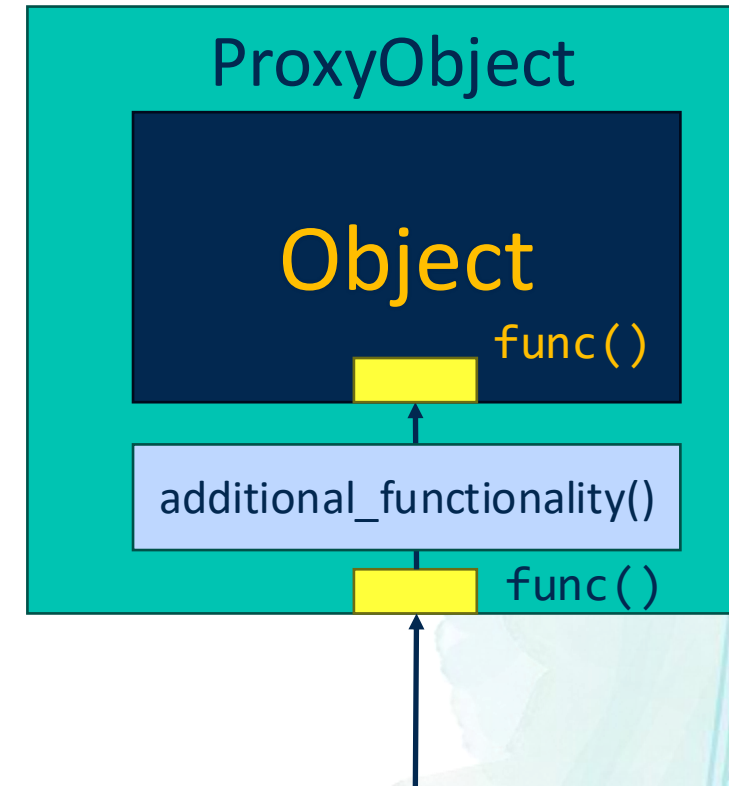
Proxies

Tapti Palit



Proxy design pattern - what is a proxy object?

- A proxy is a wrapper around the original/target object
- The user accesses the proxy object instead of the original target object
- The proxy object typically
 - Performs some additional logic
 - Then forwards the request to the target object
 - *Method interception*



The need for method “interception”

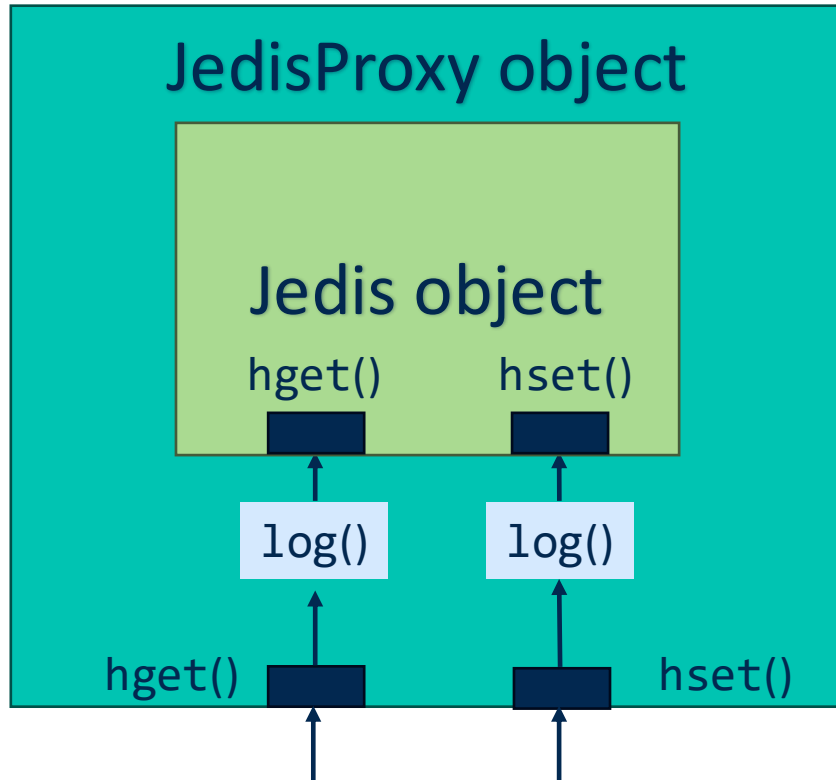
- Imagine –



- You want –

- Every time hset, hget, and hgetAll method is invoked, it should log the access on the terminal
- Challenge: can't change source code of Jedis library or the other 3rd party library

Proxy object wraps and extends target class



```
class Jedis {  
    public String hget(String id) { ... }  
    public void hset(String id, String val) { ... }  
}
```

```
class JedisProxy extends Jedis{  
    private Jedis jedis; // Wrap jedis obj
```

```
    public log() { S.o.p(...); }
```

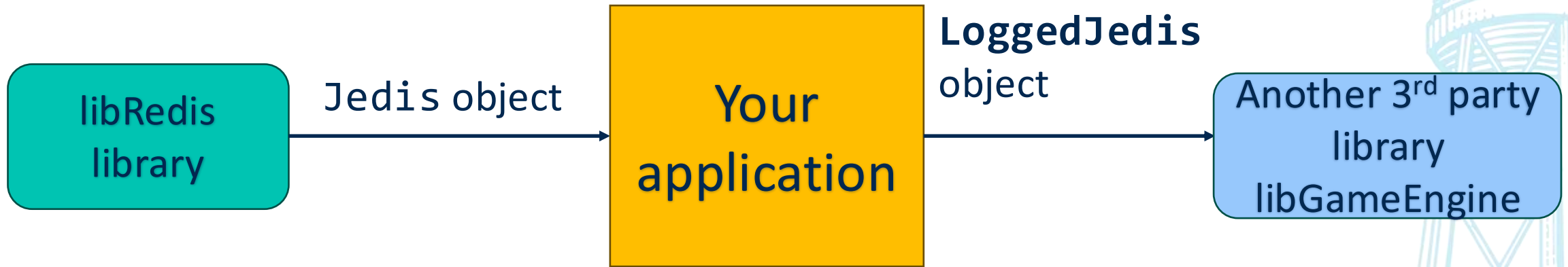
```
    public String hget(String id) {  
        log();  
        return jedis.hget(id);  
    }
```

```
    public void hset(String id, String val) {  
        log();  
        jedis.hset(id, val);  
    }
```

```
}
```

Proxies intercept the method invocations

What did we gain?



Wrap Jedis object in a LoggedJedis proxy

```
LoggedJedis loggedJedis = new LoggedJedis();  
loggedJedis.setJedis(jedis);
```

- Every hget and hset method invocation calls logging functionality
- No need to change libRedis or libGameEngine source code
- **No need to manually copy any fields**

What are the limitations?

- Explicitly create a class that wraps the original object type
- Explicitly create objects of this proxy class
- **Limitation:** proxy classes must be statically designed for each “proxyable” class
 - Duplicated logging logic

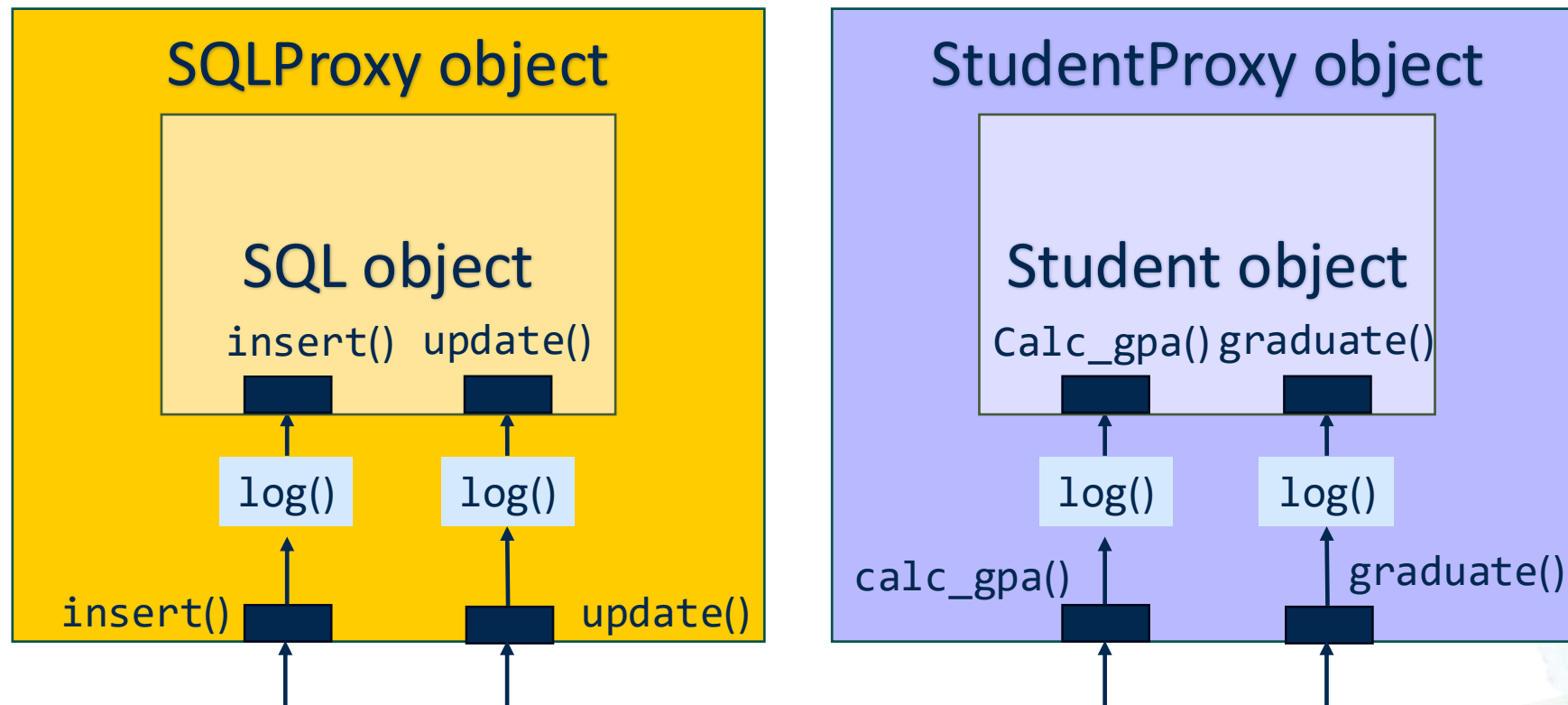
```
class SQL {  
    public void executeQuery(String query) { ... }  
}
```

```
class SQLProxy extends Query{  
    public log() { S.o.p(...); }  
  
    public void executeQuery(String query) {  
        log();  
        query.executeQuery(query);  
    }  
}
```

```
SQL sql = ...; // sql object  
SQLProxy sqlProxy = new SQLProxy(sql);
```

Duplicated work

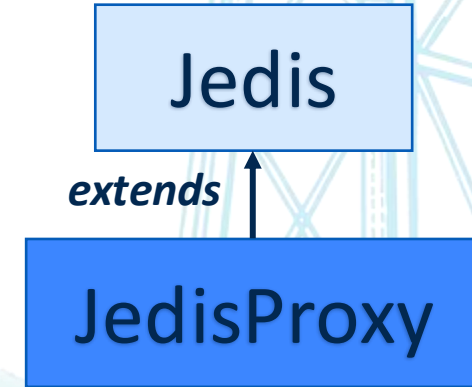
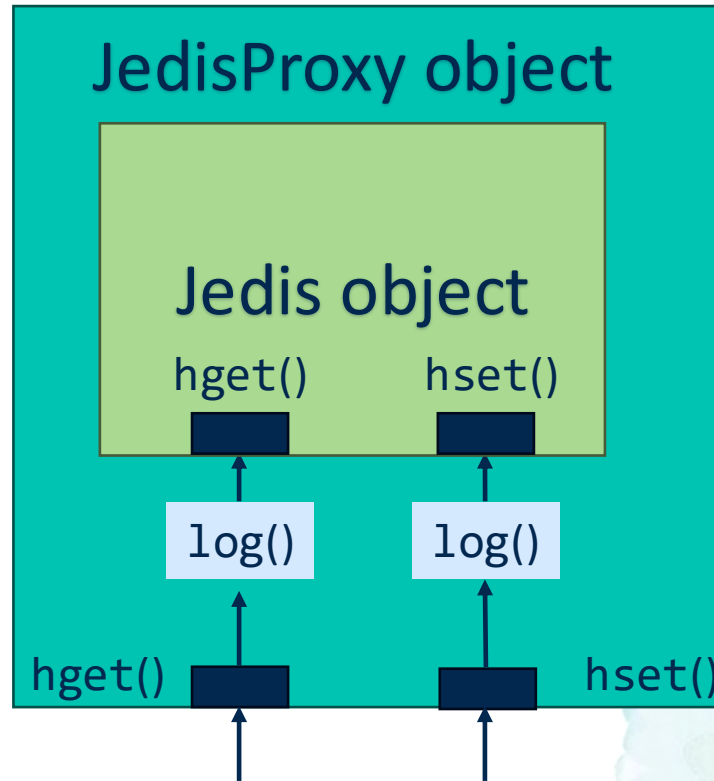
- Add logging to other classes



Duplicated work designing proxy classes for each class

Proxy goals

- Want to reuse the proxy functionality (logging, for example)
- Would be nice to **dynamically** create a **subclass** for the target object class that wraps any target object with the proxy functionality
- E.g. magical method which accepted the `log()` method and generated `JedisProxy` **on the fly**



Proxy goals

- Want to reuse the proxy functionality (logging, for example)
- Would be nice to **dynamically** create a **subclass** for the target object class that wraps any target object with the proxy functionality
- E.g. magical method which accepted the `log()` method and generated `JedisProxy` **on the fly**

```
Object createProxy(Object target, [FUNCTION  
encapsulating the additional functionality]) {
```

```
    // 1. Create proxyClass which is a subclass  
    of target.getClass()
```

```
    // 2. This proxyclass will intercept all  
    method invocations on itself
```

```
    // 3. And invoke the additional  
    functionality and then retarget them to the  
    target object
```

```
    // 4. Create and return an object of  
    proxyClass  
}
```

Runtime bytecode generation and manipulation

- ByteBuddy, Javassist libraries allow proxy creation via dynamic subclassing
 - ByteBuddy and Javassist hide bytecode manipulation complexities
 - Internally uses ASM library which gives complete bytecode generation/manipulation capabilities
- Java also has a dynamic proxy functionality
 - IMHO, it's unnecessarily complicated
 - Is an example of a language providing support for a design pattern!

Proxying using Javassist (extra-credit HW2)

- Create a ProxyFactory and set the parent class
- Implement the interface MethodHandler (possibly as an anonymous inner class)
- Override the invoke method to log
 - Then finally invoke the target object's method

```
Object createProxy(Object object) {  
    Class<?> clazz = object.getClass();
```

```
    ProxyFactory proxyFactory = new ProxyFactory();  
    proxyFactory.setSuperclass(clazz);
```

```
    MethodHandler methodHandler = new MethodHandler() {  
        @Override  
        public Object invoke(Object self,  
                             Method thisMethod,  
                             Method proceed,  
                             Object[] args) throws Throwable {  
            log("accessing method" +  
thisMethod.getName());  
            return proceed.invoke(self, args);  
        }  
    }; ...
```

**Proxy's
additional
functionality**

**All methods of object
intercepted by invoke method**

Proxying using Javassist (extra-credit HW2)

- Arguments to invoke method
 - self – the target object
 - proceed – the invoked method in the target object
 - thisMethod – the invoked method in the proxy object
 - args – any arguments passed to the method invocation

```
Object createProxy(Object object) {  
    Class<?> clazz = object.getClass();
```

```
    ProxyFactory proxyFactory = new ProxyFactory();  
    proxyFactory.setSuperclass(clazz);
```

```
    MethodHandler methodHandler = new MethodHandler() {  
        @Override  
        public Object invoke(Object self,  
                             Method thisMethod,  
                             Method proceed,  
                             Object[] args) throws Throwable {  
            log("accessing method" +  
thisMethod.getName());  
            return proceed.invoke(self, args);  
        }  
    }; ...
```

***Proxy's
additional
functionality***

***All methods of object
intercepted by invoke method***

Proxying using Javassist (extra-credit HW2)

- Create the proxy object by getting the constructor of the proxy class and invoking `newInstance` on it, using Reflection
- Set the handler
- Return the proxy object, which is a subclass of the original class type

```
Object createProxy(Object object) {  
    // ... previous slide
```

```
    Class<?> proxyClass = proxyFactory.createClass();
```

```
    Object proxyObject =  
        proxyClass.getDeclaredConstructor().newInstance();
```

```
    ((javassist.util.proxy.Proxy)  
        proxyObject).setHandler(methodHandler);
```

```
    return proxyObject;
```

```
}
```


Complete solution

```
Object createProxy(Object object) {  
    Class<?> clazz = object.getClass();
```

```
    ProxyFactory proxyFactory = new ProxyFactory();  
    proxyFactory.setSuperclass(clazz);
```

```
    MethodHandler methodHandler = new MethodHandler() {  
        @Override  
        public Object invoke(Object self,  
            Method thisMethod,  
            Method proceed,  
            Object[] args) throws Throwable {  
            log("accessing method" +  
thisMethod.getName());  
            return proceed.invoke(self, args);  
        }  
    };  
};
```

```
    Class<?> proxyClass = proxyFactory.createClass();  
    Object proxyObject =  
proxyClass.getDeclaredConstructor().newInstance();  
    ((javassist.util.proxy.Proxy)  
proxyObject).setHandler(methodHandler);  
    return proxyObject;  
}
```

```
Jedis jedis = ...;
```

```
Jedis jedisProxy = (Jedis) createProxy(jedis);  
jedisProxy.hset(...);
```

// jedisProxy has type "subclass of Jedis" and is generated at runtime
// hset will first print the log and then perform hset operation

```
Student student = ...;
```

```
Student studentProxy = createProxy(student);  
studentProxy.getName();
```

// studentProxy has type "subclass of Student" and is generated at runtime
// getName() will first print the log and then perform the getName operation

// ... Can dynamically create proxies of any
// object using createProxy() method

Demo

- https://github.com/davsec-teaching/javassist_demo



Real world use cases of proxies

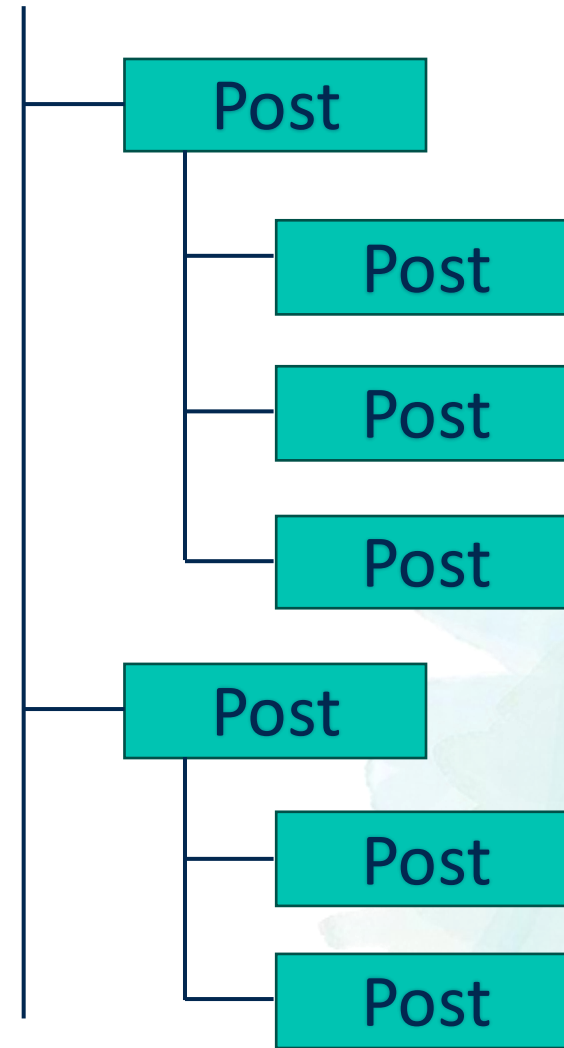
- Sample use cases
 - Lazy loading
 - Mock testing



EASYMOCK

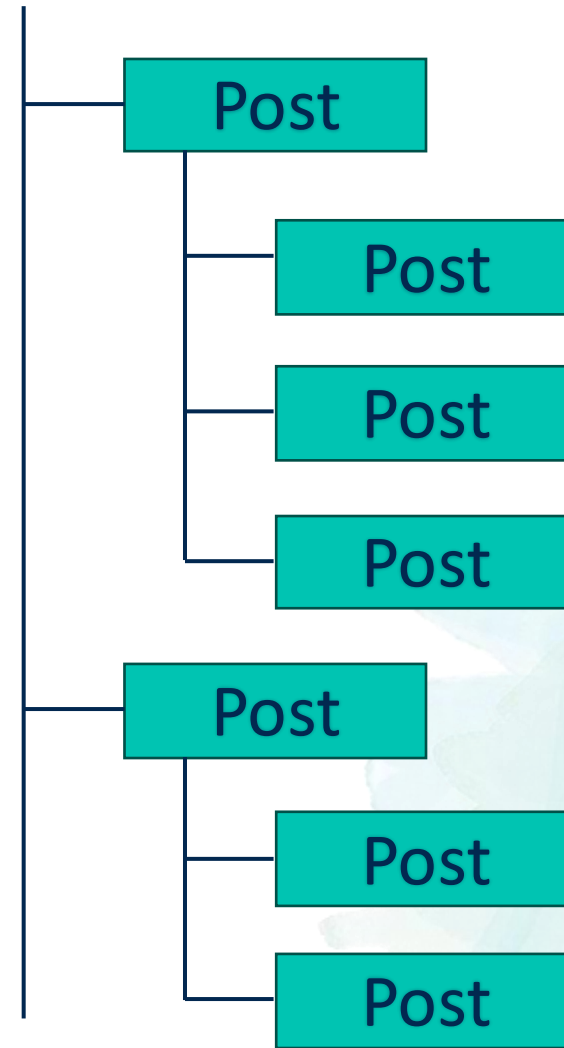
Loading posts

- Load a single post from the Redis database



Loading posts

- Load a single post from the Redis database
- High level overview
 - Load a post
 - For each reply
 - Load the reply



Loading posts from Redis

```
map = jedis.hgetAll("3208");  
Post post = new Post();  
post.setId("3208");  
post.setCreatedAt(map.get("createdAt"));
```

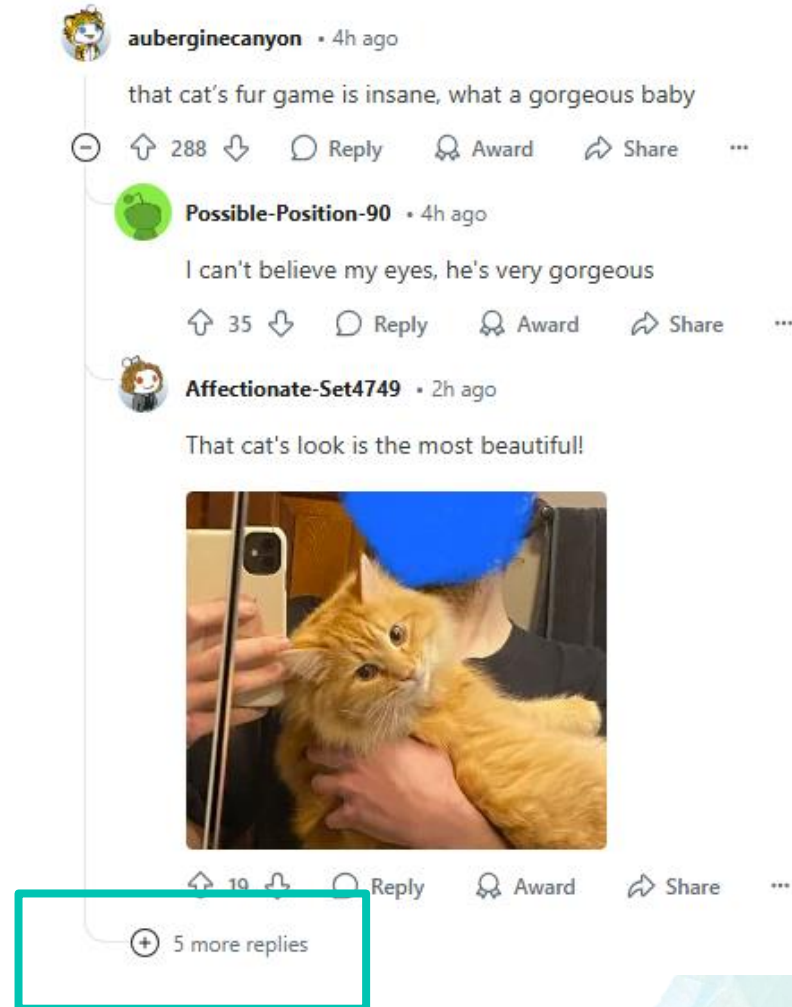
```
List<String> replies =  
map.get("childPosts").split(",");  
  
for (String replyId: replies) {  
    replyMap = jedis.hgetAll(replyId);  
    Post reply = new Post();  
    reply.setId(replyId);  
    reply.setCreatedAt(replyMap.get("createdAt"));  
    post.getReplies().add(reply);  
}
```

```
127.0.0.1:6379> hgetall 3208  
1) "children"  
2) ""  
3) "QuoteCount"  
4) "0"  
5) "Author"  
6) "Author{handle='aparker.io', name='austin \xf0\x9f\x8e\x84'}"  
7) "Id"  
8) "3176"  
9) "ReplyCount"  
10) "2"  
11) "LikeCount"  
12) "15"  
13) "PostContent"  
14) "bluesky brought to you by verisign"  
15) "RepostCount"  
16) "1"  
17) "childPosts"  
18) "3177,3188,"  
127.0.0.1:6379> |
```

All replies loaded when the post is loaded

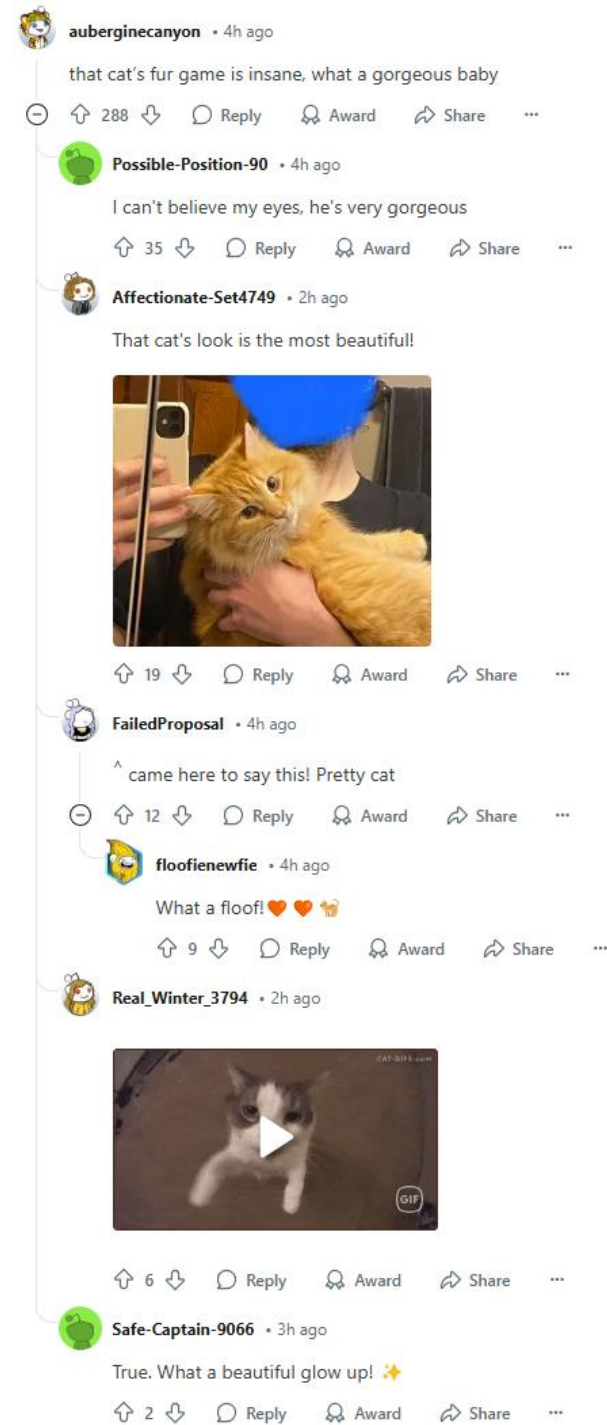
Lazy loading posts UI

- Common performance improvement
- Replies are loaded only when user indicates they want to see the replies
- Improves UI responsiveness



Lazy loading

- Common performance improvement
- Replies are loaded only when user indicates they want to see the replies
- Clicking on '+' loads the remaining replies



Mock UI code for posts

- Imagine this is a single application
 - Ignore network for a moment
- Java UI
 - Window, Button
- Java objects of type Post

```
class UIButton {  
    void onClick() {  
        // event handler to be triggered on click  
    }  
}
```

```
class UIWindow {  
    // ...  
}
```

```
class Post {  
    private String content;  
    private String createdAt;  
    private List<Post> replies;  
  
    // getters and setters  
    List<Post> getReplies() {return replies; }  
}
```

```
public static void main(String[] args) {  
    Post post = loadPost("3208");  
    UIWindow window = new UIWindow();  
    window.add(new UIText(post.getContent()));  
    window.add(new UIButton("+"));  
}
```


Lazy loading replies

- Idea
 - loadPost only loads the post
 - Replies loaded from database when the button is clicked
 - onClick event is triggered

```
class UIButton {  
    void onClick() {  
        // event handler to be triggered on click  
    }  
}  
  
class UIWindow {  
    // ...  
}  
  
class Post {  
    private String content;  
    private String createdAt;  
    private List<Post> replies;  
  
    // getters and setters  
    List<Post> getReplies() {return replies; }  
}  
  
public static void main(String[] args) {  
    Post post = loadPost("3208");  
    UIWindow window = new UIWindow();  
    window.add(new UIText(post.getContent()));  
    window.add(new UIButton("+"));  
}
```


Lazy loading replies

- Original loadPost method
- How many database accesses?

```
// original loadPost method
```

```
Post loadPost(String id) {  
    map = jedis.hgetAll(id);  
    Post post = new Post();  
    post.setId(id);  
    post.setCreatedAt(map.get("createdAt"));
```

```
    List<String> replies =  
        map.get("childPosts").split(",");
```

```
    for (String replyId: replies) {  
        replyMap = jedis.hgetAll(replyId);  
        Post reply = new Post();  
        reply.setId(replyId);  
        reply.setCreatedAt(replyMap.get("createdAt"));  
        post.getReplies().add(reply);  
    }  
    return post;  
}
```

Lazy loading replies

- loadPost method with lazy loading
 - Only load the post fields and the ids of the replies
- How many database accesses?
- Much faster (even more so for on-disk SQL databases)

// original loadPost method

```
Post loadPost(String id) {  
    map = jedis.hgetAll(id);  
    Post post = new Post();  
    post.setId(id);  
    post.setCreatedAt(map.get("createdAt"));
```

```
    List<String> replies =  
        map.get("childPosts").split(",");
```

```
    for (String replyId: replies) {  
        replyMap = jedis.hgetAll(replyId);  
        Post reply = new Post();  
        reply.setId(replyId);  
        reply.setCreatedAt(replyMap.get("createdAt"));  
        post.getReplies().add(reply);  
    }  
    return post;  
}
```

Lazy loading replies

- `onClick` fetches the replies only if the button is clicked
- Fetch all the replies
- Draw them on the UI Window

```
class UIButton {  
    Post post;  
    void onClick() {  
        for (Reply reply: post.getReplies()) {  
            // only the id is populated, so must  
            // invoke loadPost  
            Reply reply = loadPost(reply.getId());  
            window.add(new UIText(reply.getContent()));  
        }  
    }  
}  
  
class UIWindow {  
    // ...  
}
```

Problem

- UI designers shouldn't have to worry about backend concerns
- Shouldn't have to know which method to know which method to invoke to load the reply
- Only `window.add(new UIText(reply.getContent()));`
- How to achieve this?

```
class UIButton {
    Post post;
    void onClick() {
        for (Reply reply: post.getReplies()) {
            // only the id is populated, so must
            // invoke loadPost
            Reply reply = loadPost(reply.getId());
            window.add(new UIText(reply.getContent()));
        }
    }
}

class UIWindow {
    // ...
}
```


An option ...

- Stick the lazy loading logic in the Post class
- Terrible, terrible idea!!
- Assume that posts are always lazy loaded
- Assume that posts are always loaded from the database
- Breaks all reusability
- Breaks SRP

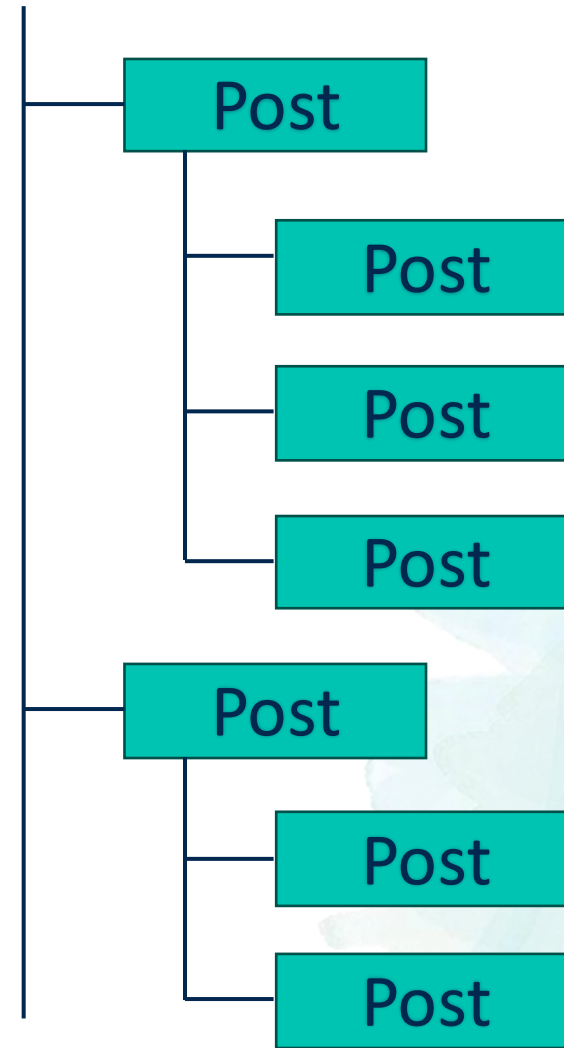
```
class Post {  
    private String content;  
    private String createdAt;  
    private List<Post> replies;  
  
    // getters and setters  
    List<Post> getReplies() {  
        List<Post> newReplies = ...;  
        for (Reply reply: this.getReplies()) {  
            // only the id is populated  
            Reply reply = loadPost(reply.getId());  
            newReplies.add(reply);  
        }  
        this.setReplies(newReplies);  
    }  
}
```


Dynamic proxy use cases



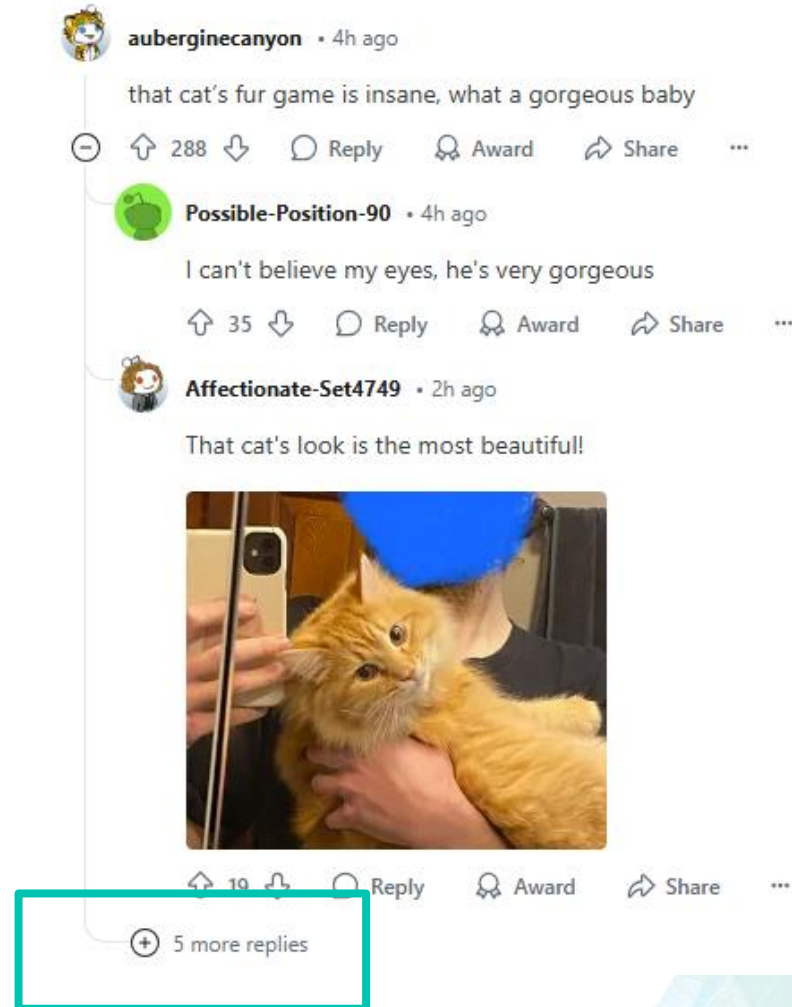
Loading posts

- Load a single post from the Redis database
- High level overview
 - Load a post
 - For each reply
 - Load the reply



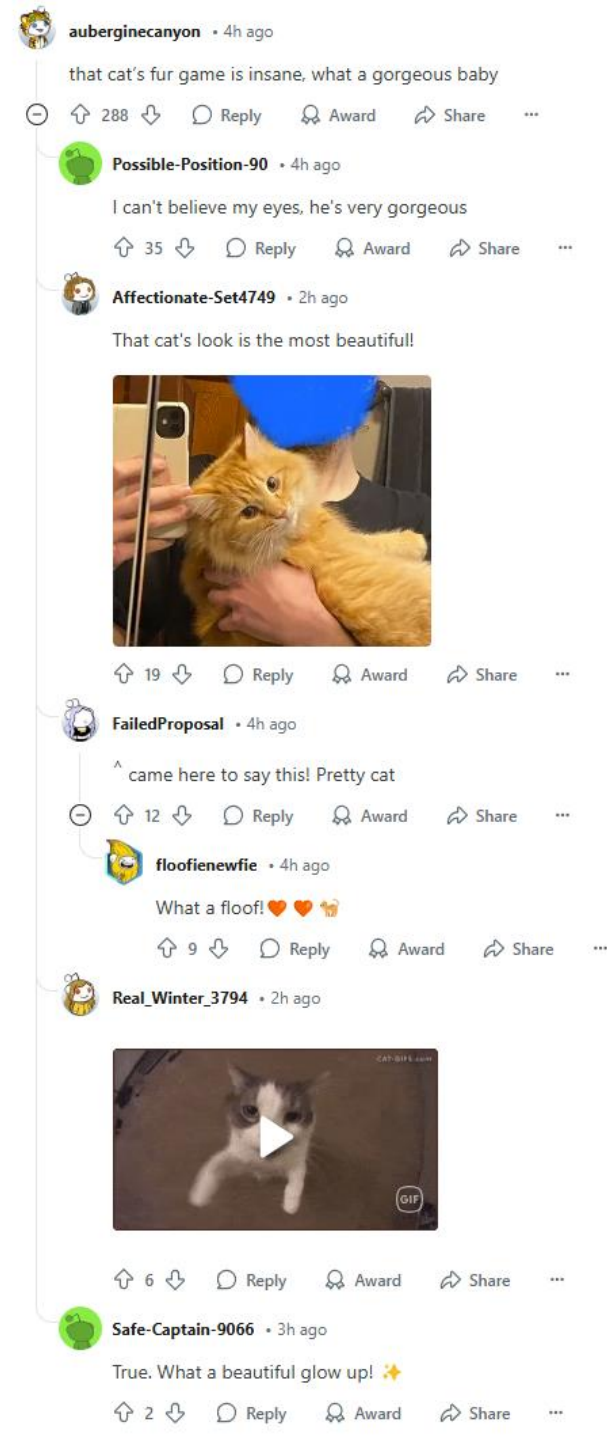
Lazy loading posts UI

- Common performance improvement
- Replies are loaded only when user indicates they want to see the replies
- Clicking on '+' loads the remaining replies



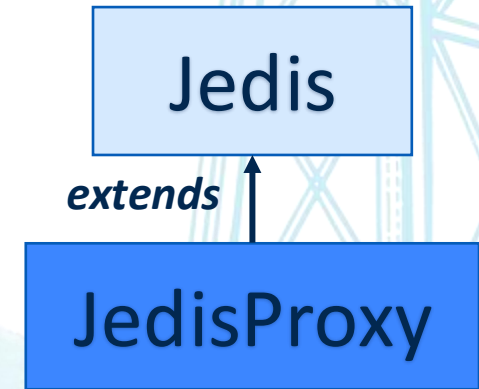
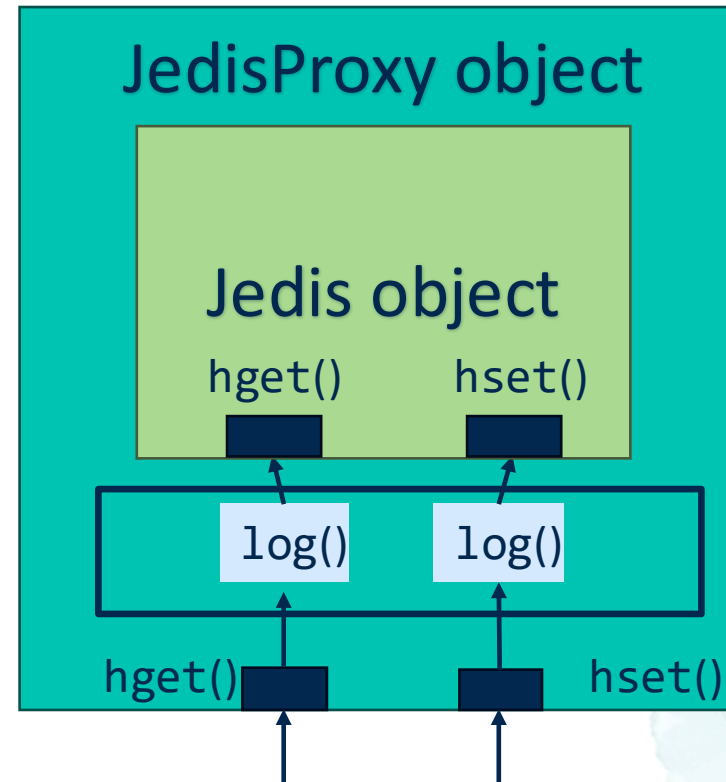
Lazy loading

- Clicking on '+' loads the remaining replies
- Dynamic proxies simplify implementing lazy loading
- This class: *sketch of a solution (not full solution)*



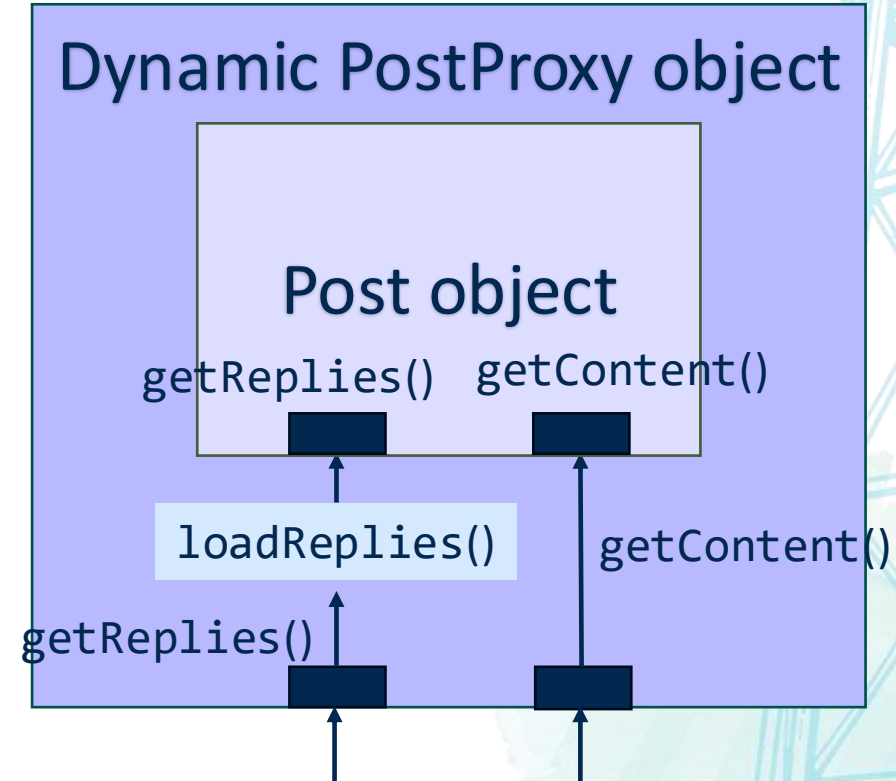
Proxies: recap

- A proxy is a wrapper around a target object
- The proxy intercepts method invocations
 - Performs additional functionality
 - Dispatches the method to the target object
- Proxy class extends target class
 - Allows proxy to replace the target object for all uses



Proxies for lazy loading

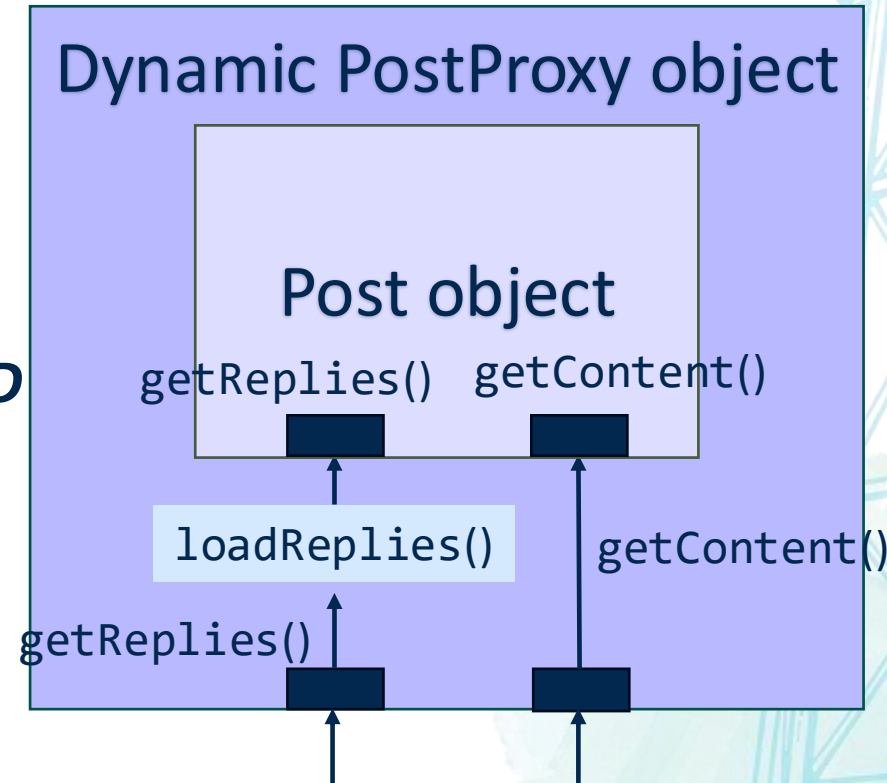
- High level approach
 - Create reply Post objects with only the postId (do not load the data using `hgetAll()`)
 - Create a dynamic proxy for the Post object and have it intercept `getReplies()` method invocation
 - Only when the `getReplies()` method is invoked, perform `loadReplies()` to load all the reply post objects



Proxies for lazy loading

```
Post loadPost(String id) {  
    map = jedis.hgetAll(id);  
    Post post = new Post();  
    post.setId(id);  
    post.setCreatedAt(map.get("createdAt"));  
  
    List<String> replies =  
        map.get("childPosts").split(",");  
  
    for (String replyId: replies) {  
        Post reply = new Post();  
        // does not load the reply details  
        reply.setId(replyId);  
        post.getReplies().add(reply);  
    }  
    return createLazyLoadProxy(post);  
}
```

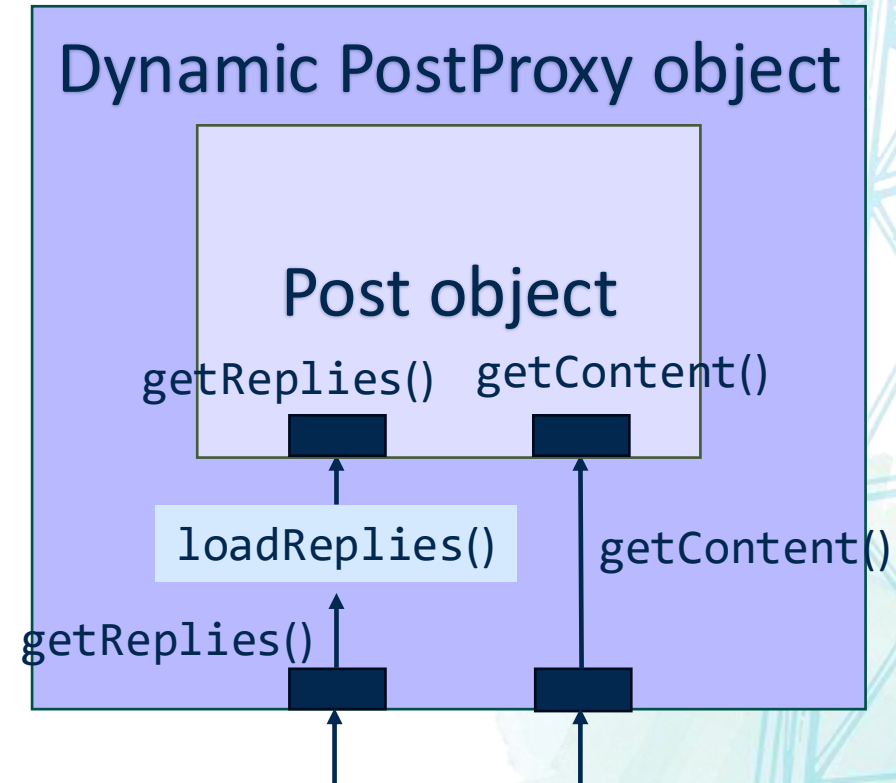
Only set the Reply ID



Proxies for lazy loading

```
list<Post> loadReplies() {  
    List<Post> newReplies = ...;  
    for (Reply reply: this.getReplies()) {  
        // only the id is populated  
        Reply reply = loadPost(reply.getId());  
        newReplies.add(reply);  
    }  
    this.setReplies(newReplies);  
}
```

Proxy calls loadReplies transparently



Lazy loading code is provided by the proxy class

Proxies for lazy loading

```
Object createLazyLoadProxy(Object target) {  
    Class<?> clazz = object.getClass();  
    ProxyFactory proxyFactory = new ProxyFactory();  
    proxyFactory.setSuperclass(clazz);
```

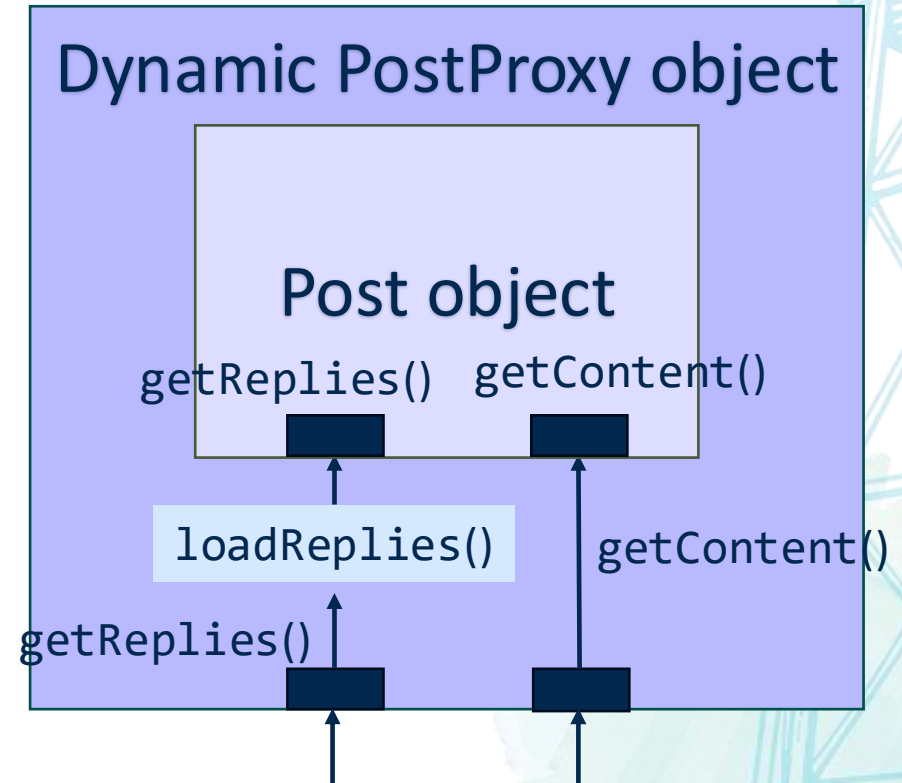
Create PostProxy objects

```
    MethodHandler methodHandler = new  
    LazyLoadMethodHandler(target);
```

```
    Class<?> proxyClass =  
    proxyFactory.createClass();  
    Object proxyObject =  
    proxyClass.getDeclaredConstructor().newInstance();  
    ((javassist.util.proxy.Proxy)  
    proxyObject).setHandler(methodHandler);  
    return proxyObject;  
}
```

```
class MyMethodHandler extends MethodHandler {  
    private Object target;  
    public Object invoke(...) throws Throwable {  
        // Code to invoke loadReplies();  
        // if getReplies() is invoked  
        return proceed.invoke(target, args);  
    }  
}
```

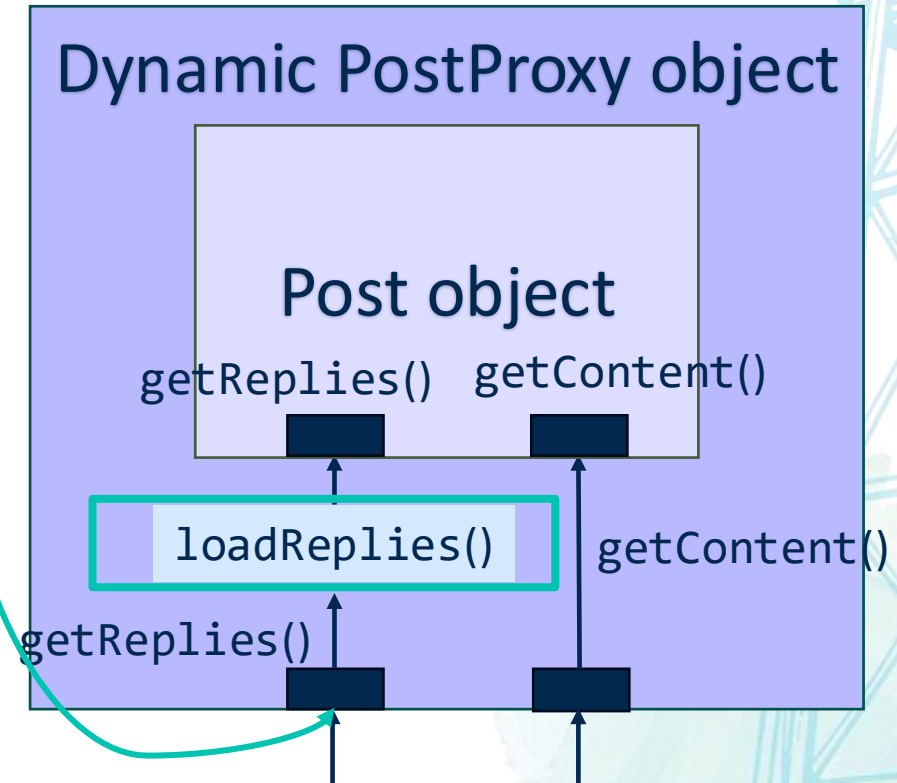
Invoke loadReplies()



createLazyLoadProxy returns the proxy object

Proxies for lazy loading

```
class UIButton {  
    Post post;  
    void onClick() { post is a proxy object  
        for (Reply reply: post.getReplies()) {  
            Reply reply = loadPost(reply.getId());  
            window.add(new UIText(reply.getContent()));  
        }  
    }  
}  
  
class UIWindow {  
    // ...  
}  
  
public static void main(String[] args) {  
    Post post = loadPost("3208");  
    UIWindow window = new UIWindow();  
    window.add(new UIText(post.getContent()));  
    window.add(new UIButton("+"));  
}
```



Reflection + annotations + dynamic proxies

- Can combine proxies with reflection and annotation
- Lazy loading only for annotated fields
 - Load the `@LazyLoad` annotated fields only when their getter is invoked
- ***Transparent*** lazy load from the programmer's perspective

```
class Post {  
    @Persistable  
    Integer postId;  
    @Persistable  
    String postContent;  
    @Persistable  
    @LazyLoad  
    List<Post> replies;  
  
    // getters and setters for postId,  
    postContent, replies  
    // All methods intercepted by dynamic proxy  
    // replies lazy loaded by the dynamic proxy  
}
```

Lazy loading

- Database records
 - All ORMs such as Hibernate support lazy loading using annotations
- File content
 - Lazy load 1 GB file
- Content to be fetched over the network
 - Lazy load remote content



Proxies for mock testing

Mocking overview

- What is mocking?
 - Simulate the behavior of real objects in a controlled way
- Useful during unit-testing
- Why?
 - Isolate components for unit testing
 - External systems (APIs, Databases)
 - Complex or time-consuming operations



Mocking overview

- Example: unit test `composeEmail`
- But don't want to actually send an email to a client!!

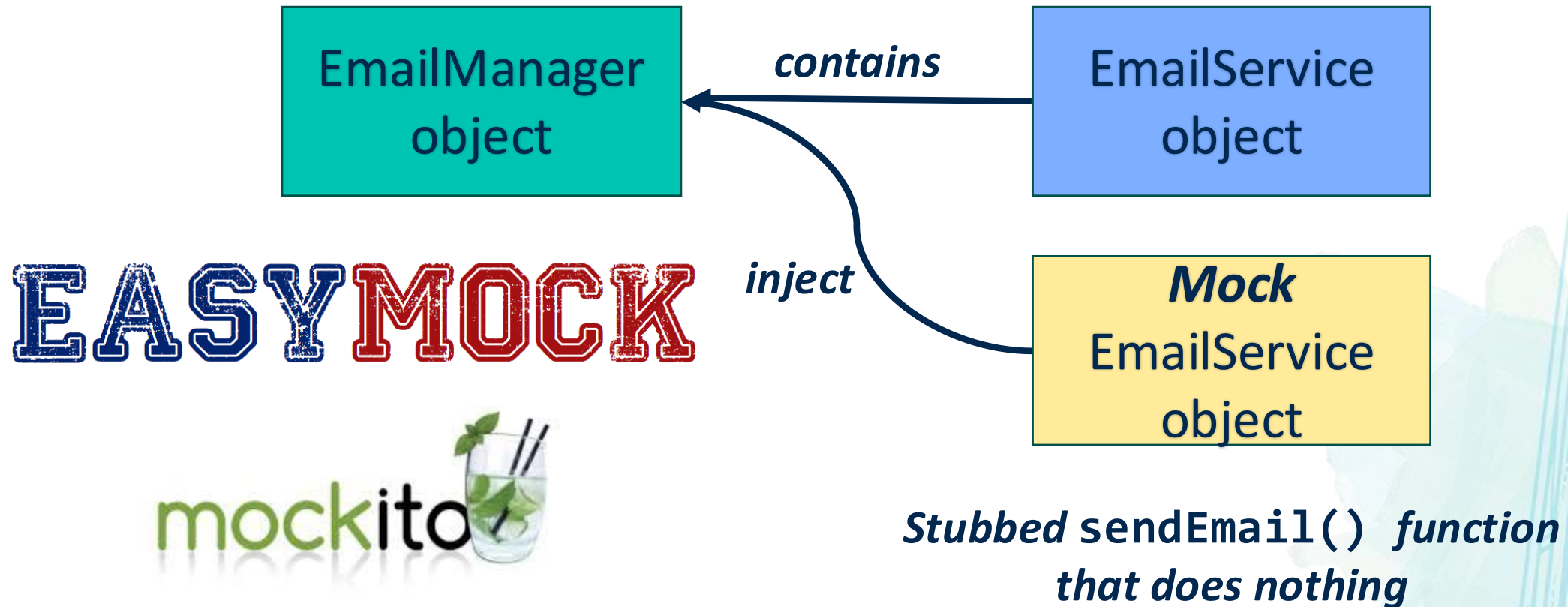
```
public EmailService {  
    public boolean sendEmail(...) {  
        // send an email  
        if (success) return true;  
        return false;  
    }  
}
```

```
public class EmailManager {  
    private EmailService emailService;  
  
    private void formatEmail(String email) { ... }  
    private void displayError(boolean succ) { ... }
```

```
    public String composeEmail(...) {  
        String email = ...;  
        formatEmail(email);  
        boolean success = emailService.send(email);  
        displayError(success);  
    }  
}
```

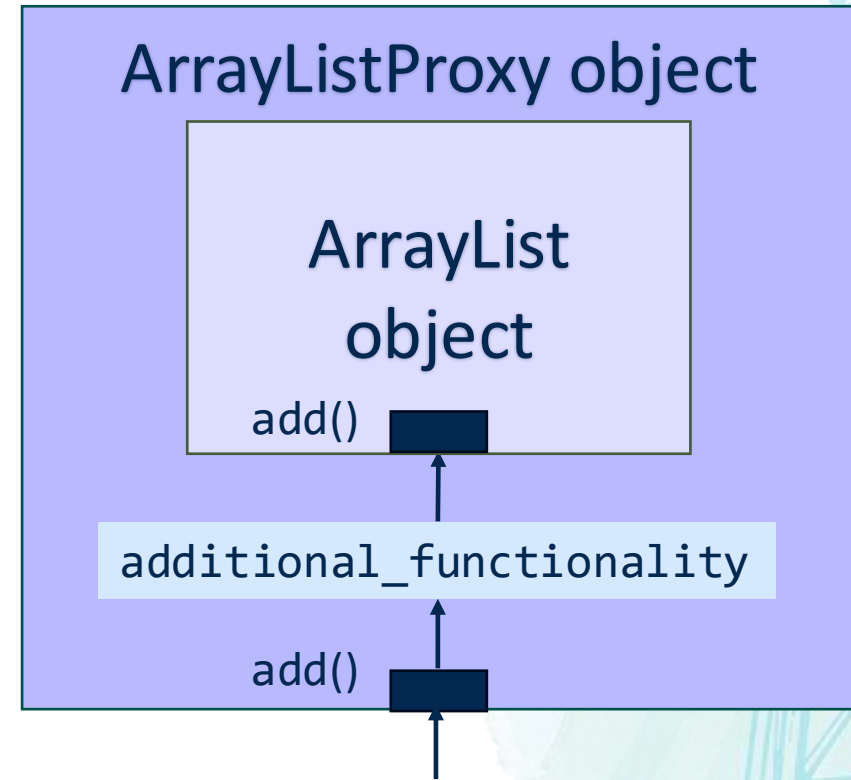
Mockito overview

Allows programmer to inject mock objects to ***stub*** functionality



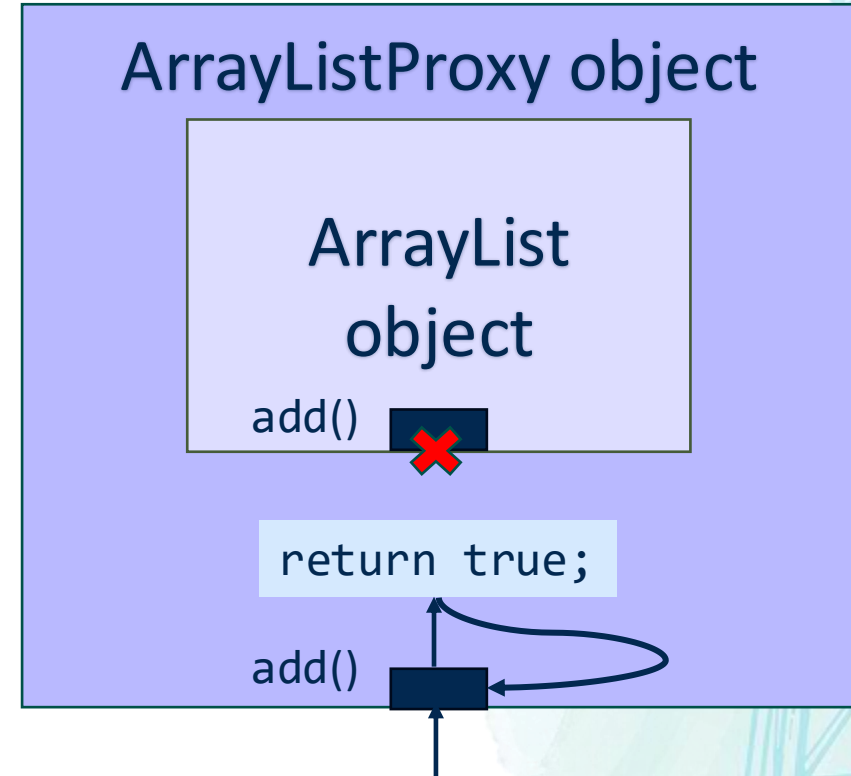
Proxy can hijack functionality

- Previous cases proxies augmented the target object functionality



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- Previous cases proxies augmented the target object functionality
- It can also hijack functionality and not invoke the target object's method
- ArrayList proxy object can always return true for add() invocation



Proxy can hijack functionality

- Previous cases proxies augmented the target object functionality
- It can also hijack functionality and not invoke the target object's method
- ArrayList proxy object can always return true for add() invocation

```
Object createProxy(Object object) {
    Class<?> clazz = object.getClass();

    ProxyFactory proxyFactory = new ProxyFactory();
    proxyFactory.setSuperclass(clazz);

    MethodHandler methodHandler = new MethodHandler() {
        @Override
        public Object invoke(Object self,
            Method thisMethod,
            Method proceed,
            Object[] args) throws Throwable {
            log("accessing method" +
                thisMethod.getName());
            return proceed.invoke(self, args);
            return new Boolean(true);
        }
    };

    Class<?> proxyClass = proxyFactory.createClass();
    Object proxyObject =
        proxyClass.getDeclaredConstructor().newInstance();
    ((javassist.util.proxy.Proxy)
        proxyObject).setHandler(methodHandler);
    return proxyObject;
}
```

Mock an ArrayList

- Mockito's `mock()` method injects a proxy
- Configure the proxy object
 - `when`
 - `thenReturn`

```
import java.util.List;

import static
org.mockito.ArgumentMatchers.anyInt;
import static org.mockito.Mockito.mock;
import static org.mockito.Mockito.when;

public class MyApp {
    public static void main(String[] args) {
        List<Number> myList =
mock(ArrayList.class);
        when(myList.add(10)).thenReturn(true);

when(myList.add(anyInt())).thenReturn(false);

        System.out.println(myList.add(30)); //
return false
        System.out.println(myList.add(10)); //
return true

    }
}
```

Mock an ArrayList

- Mockito's `mock()` method injects a proxy
- Configure the proxy object
 - `when`
 - `thenReturn`
- Mockito proxy objects record method invocations the first time
 - Then replay the configured return value

```
import java.util.List;

import static
    org.mockito.ArgumentMatchers.anyInt;
import static org.mockito.Mockito.mock;
import static org.mockito.Mockito.when;

public class MyApp {
    public static void main(String[] args) {
        List<Number> myList =
            mock(ArrayList.class);
        when(myList.add(10)).thenReturn(true);

        when(myList.add(anyInt())).thenReturn(false);

        System.out.println(myList.add(30)); //
        return false
        System.out.println(myList.add(10)); //
        return true

    }
}
```

Writing a JUnit test with Mockito

```
public EmailService {
    public boolean sendEmail(...) {
        // send an email
        if (success) return true;
        return false;
    }
}

public class EmailManager {
    private EmailService emailService;

    private void formatEmail(String email) { ... }
    private void displayError(boolean succ) { ...}

    public String composeEmail(...) {
        String email = ...;
        formatEmail(email);
        boolean success = emailService.send(email);
        displayError(success);
    }
}
```

```
import ...;

public class EmailManagerTest {
    @Mock
    private EmailService emailService;

    @InjectMocks
    private EmailManager emailManager;

    @BeforeEach
    public void setUp() {
        MockitoAnnotations.openMocks(this); // Initialize
        mocks
    }

    @Test
    public void testComposeEmail() {
        // Stub the sendEmail method to return true
        when(emailService.sendEmail(anyString())).thenReturn(true);

        // Call the method under test
        String result = emailManager.composeEmail();
        // do any assertion checks
    }
}
```


Concluding points

- Reflection, annotations, and dynamic proxies are very powerful
 - Must be used judiciously
 - Typically, not used in regular application development
 - Used in framework development



Concluding points

- Frameworks using reflection, annotations, and dynamic proxies are widely used
- Beneficial to know how they work under-the-hood
- Very helpful in debugging

```
@Entity
class InsuranceClient {
    @Id
    private Integer insuranceClientId;

    @Column(name = "address")
    private String address;

    @OneToMany(fetch = FetchType.LAZY)
    List<Policy> policies;

    // getters and setters
}

InsuranceClient client = ...;
client.getPolicies(); // sometimes takes seconds
// Why?
```

Summary

- Problem: `persist()` method had to be duplicated for each class
- Reflection allows for dynamic field access and method invocation
 - Partially solved the problem

```
class Post { }

class RedisDB {
    Jedis jedisSession;
    static int id;
    static {
        jedisSession = new Jedis("localhost",
6379);
        id = 0;
    }

    public void persist(Post post) {
        map.put("authorName", post.getAuthor());
        map.put(..., ...);
        // ... All relevant fields
        jedis.hset(id++, map);
    }

    public void persist(Student student) {
        map.put("studentName", student.getName());
        map.put(..., ...);
        // ... All relevant fields
        jedis.hset(id++, map);
    }
}
```

Summary

- Problem: `persist()` method had to be duplicated for each class
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 - Partially solved the problem

```
class Post { }

class RedisDB {
    Jedis jedisSession;
    static int id;
    static {
        jedisSession = new Jedis("localhost", 6379);
        id = 0;
    }
}
```

```
public void persistAll(Object obj) {
    Map<String, String> postMap;
    for (Field f: obj.getDeclaredFields()) {
        String fieldname = f.getName();
        Object fieldVal = f.get(obj);
        postMap.put(fieldname, fieldVal);
    }
    jedis.hset(id++, postMap);
}
```

```
}
```

```
Post p = new Post("Hello world", "1/23/2025");
Car c = new Car("BMW");
RedisDB db = new RedisDB();
db.persistAll(p);
db.persistAll(c);
```

Summary

- Problem: what if we don't want to persist all fields in an object?
- Annotations allow adding meta-data to fields, methods, etc.
- Annotations with `Retention.RUNTIME` are available at runtime
- Annotating individual fields allows us to selectively persist

```
@retention(Retention.RUNTIME)  
@interface Persistable {}
```

```
class Post {
```

```
    @Persistable  
    Object postId;
```

```
    @Persistable  
    String postContent;
```

```
    @Persistable  
    String authorName;
```

```
    Integer tempField;
```

```
}
```


Summary

- Problem: what if I want to *lazy-load* one or more fields
- Dynamic proxies allow us to intercept method invocation
 - Allowing lazy-loading of fields only when the field is accessed

```
@retention(Retention.RUNTIME)
@interface Persistable {}
```

```
class Post {

    @Persistable
    Object postId;

    @Persistable
    String postContent;

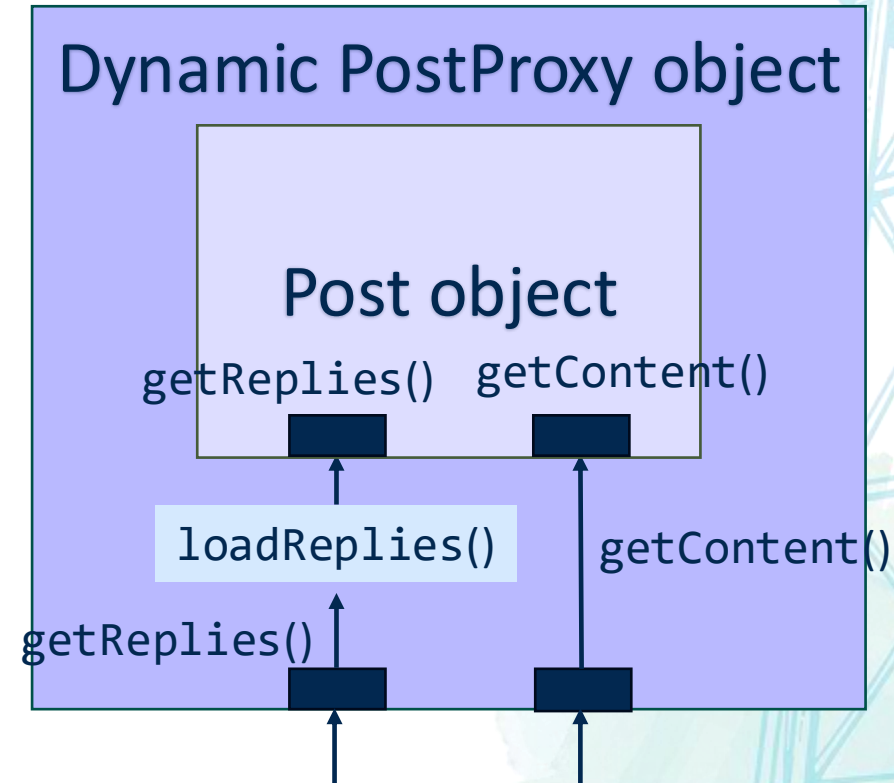
    @Persistable
    String authorName;

    @Persistable
    @LazyLoad
    List<Post> replies;

    Integer tempField;
}
```

Summary

- Problem: what if I want to *lazy-load* one or more fields
- Dynamic proxies allow us to intercept method invocation
 - Allowing lazy-loading of fields only when the field is accessed



Summary

- Reflection and proxies have application way beyond just Redis persistence and logging
- Used in microservice frameworks, MVC frameworks, dependency injection, database persistence, and so on, in many languages

