Finding Java Deserialization Gadgets with CodeQL

Automating Security Analysis for Gadget Chain Discovery

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Background

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Security Issue: Untrusted data can trigger arbitrary code execution

The Gadget Chain Concept

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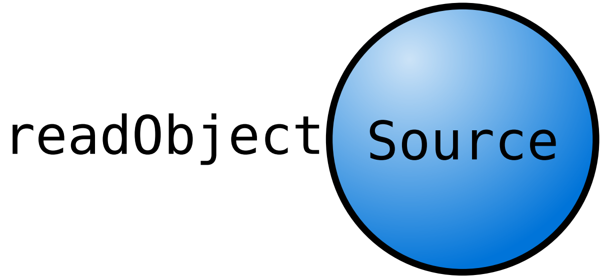

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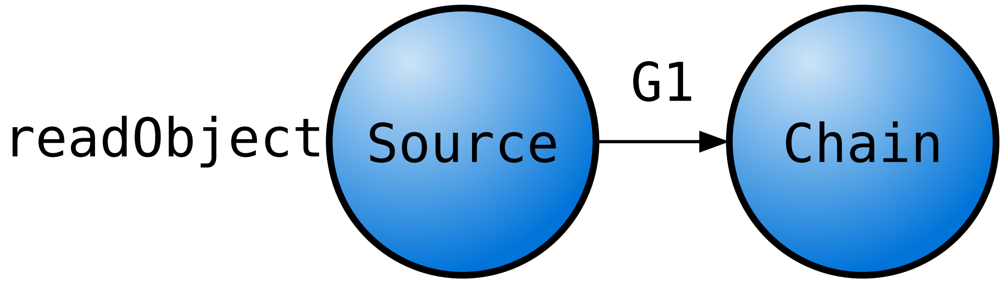

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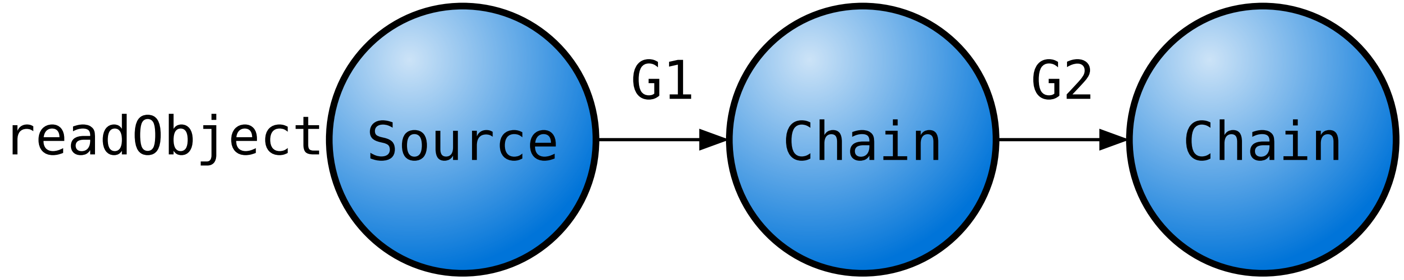

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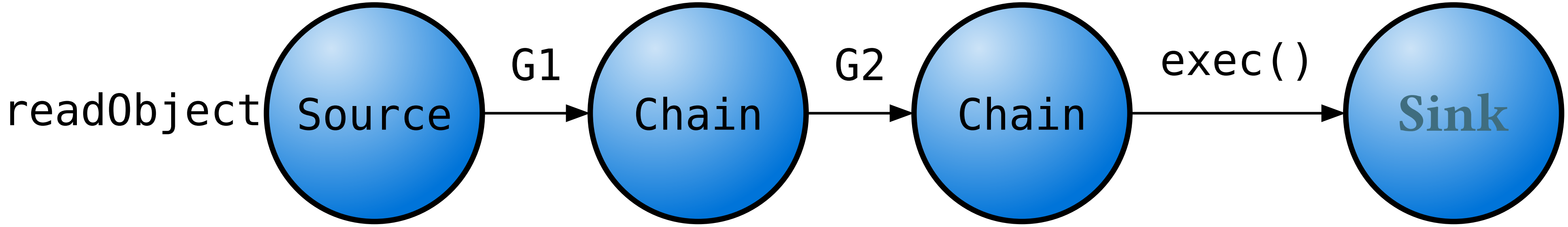

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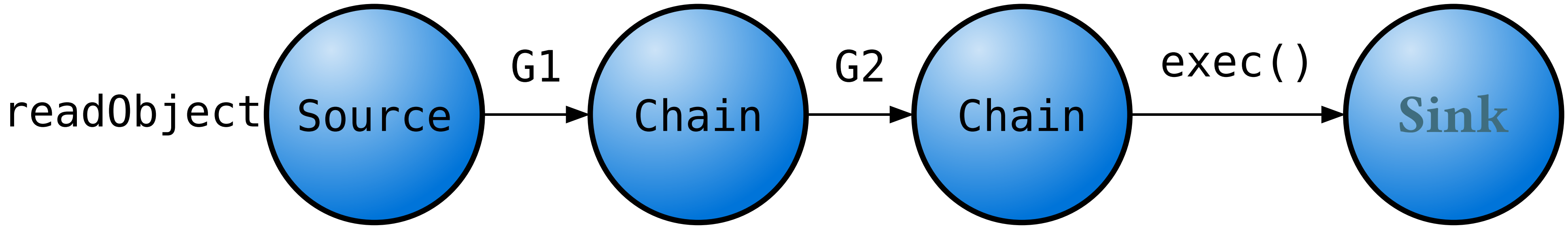

- Leverages existing classes on the classpath
- No need to inject new code - just arranges existing functionality
- Property-Oriented Programming (POP)

Why This Matters

Critical Security Impact:

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Wide Attack Surface:

- Java RMI (Remote Method Invocation)
- JMX (Java Management Extensions)
- Message queues (JMS, Spring AMQP)
- Web frameworks (Spring, Struts)

Famous Vulnerabilities

Apache Commons Collections

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- InvokerTransformer gadget
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Spring Framework

- CVE-2016-1000027 - HttpInvoker
- CVE-2023-34040 - Spring-Kafka
- Multiple gadget chains discovered

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- `ysoserial` - Payload generator (requires known gadgets)
- Manual code review (time-consuming, error-prone)
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Solution: CodeQL - Automated semantic code analysis

CodeQL Introduction

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from MethodAccess call
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Think of it as: SQL for code, but with understanding of program semantics

Key Capabilities

1. Data Flow Analysis

- Track how data moves through the program
- Identify sources (input) and sinks (dangerous operations)

2. Taint Tracking

- Follow untrusted data from entry points to sensitive operations
- Understand data transformations

Key Capabilities

3. Control Flow Analysis

- Understand execution paths
- Identify reachable code

4. Cross-Project Analysis

- Analyze entire dependency trees
- Find vulnerabilities in third-party libraries

CodeQL Architecture

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codeql database analyze myapp-db query.ql
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1. **Create Database** - Extract semantic information from source code

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codeql database create myapp-db --language=java
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2. **Write/Run Queries** - Query the database for patterns

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codeql database analyze myapp-db query.ql
```

3. **Analyze Results** - Review findings and validate

```
# Results in SARIF format for integration
```

CodeQL for Deserialization

Built-in Deserialization Detection

CodeQL includes `java/unsafe-deserialization` query

```
/**
 * @name Unsafe deserialization
 * @description Deserializing user-controlled data may allow
 *              attackers to execute arbitrary code
 * @kind path-problem
 * @id java/unsafe-deserialization
 */
import java
import semmle.code.java.dataflow.FlowSources
import semmle.code.java.security.UnsafeDeserializationQuery
```

Understanding Sources and Sinks

Source: Where untrusted data enters the system

```
predicate isSource(DataFlow::Node source) {
  source instanceof RemoteFlowSource
  // HTTP requests, socket input, etc.
}
```

Understanding Sources and Sinks

Sink: Dangerous operation that should not receive untrusted data

```
predicate isSink(DataFlow::Node sink) {
  exists(MethodAccess ma |
    ma.getMethod().hasName("readObject") and
    ma.getMethod().getDeclaringType()
      .hasQualifiedName("java.io", "ObjectInputStream") and
    sink.asExpr() = ma.getQualifier()
  )
}
```

Taint Tracking Configuration

```
import java
import semmle.code.java.dataflow.TaintTracking
module DeserializationConfig implements DataFlow::ConfigSig {
  predicate isSource(DataFlow::Node source) {
    source instanceof RemoteFlowSource}
  predicate isSink(DataFlow::Node sink) {
    exists(MethodAccess ma |
      ma.getMethod().hasName("readObject") and
      sink.asExpr() = ma.getQualifier()
    )}}
```

Finding Gadget Chains

QLinspector - Advanced CodeQL queries by Synacktiv

GitHub: github.com/synacktiv/QLinspector

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Available Queries:

- `QLinspector.ql` - Main gadget chain finder
- `BeanFactoryGadgetFinder.ql` - JNDI injection chains
- `CommonsBeanutilsGadgetFinder.ql` - Alternative gadgets
- `ObjectFactoryFinder.ql` - BeanFactory alternatives

QLinspector Usage

Step 1: Create CodeQL Database

```
codeql database create target-app-db --language=java
```

Step 2: Run QLinspector Query

```
codeql database analyze target-app-db \
  --format=sarif-latest \
  --output=results.sarif \
  ./QLinspector/QLinspector.ql
```

Step 3: Review Results

Finding Runtime.exec Sinks

Track execution sinks reachable from deserialization:

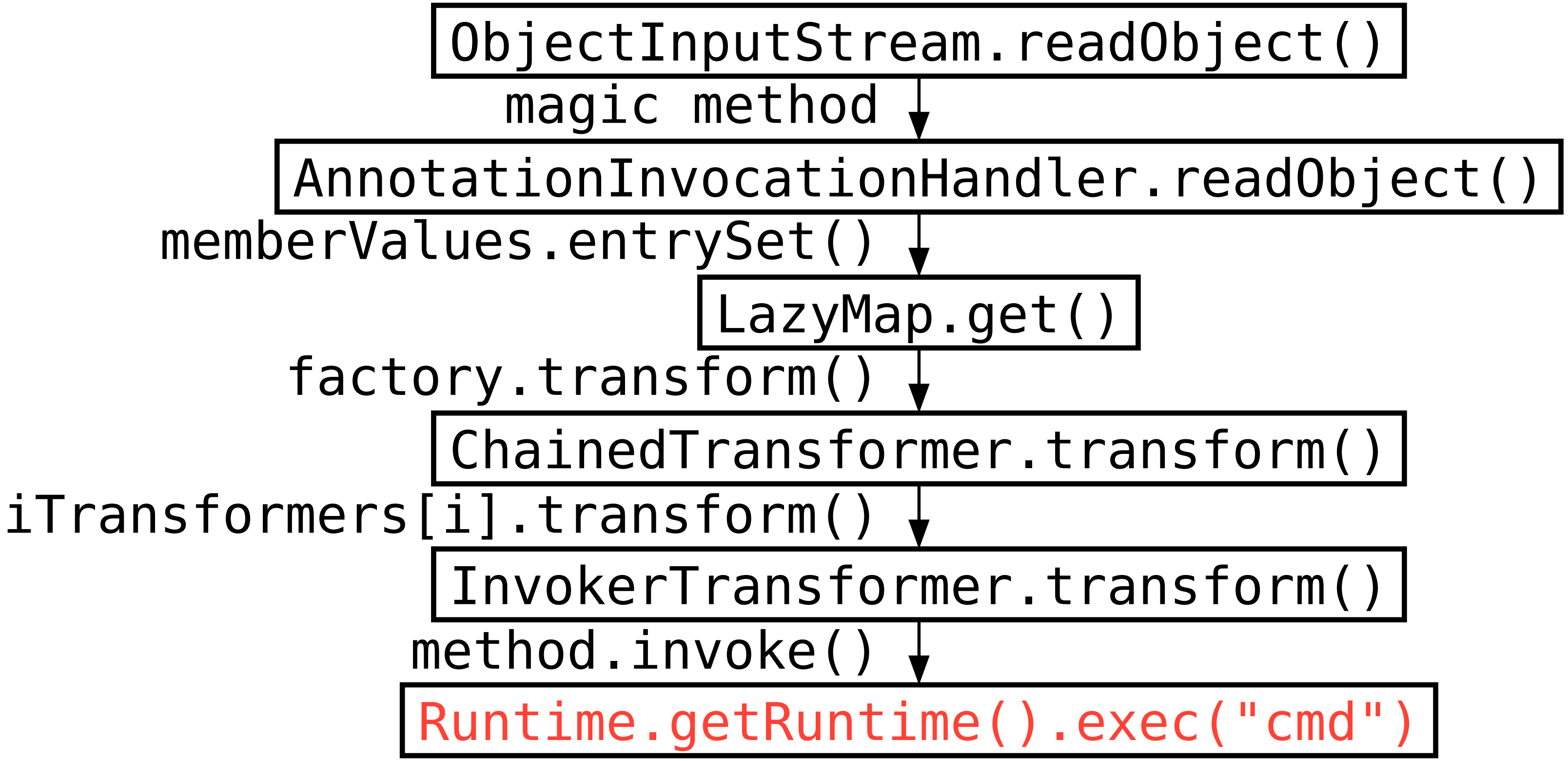
```
import java
class RuntimeExecCall extends MethodAccess {
  RuntimeExecCall() {
    this.getMethod().hasName("exec") and
    this.getMethod().getDeclaringType()
      .hasQualifiedName("java.lang", "Runtime")
  }
}
```

Finding Runtime.exec Sinks

```
from RuntimeExecCall exec
where exists(Method m |
  m.hasName("readObject") and
  exec.getEnclosingCallable().calls*(m)
)
select exec, "Potential gadget chain to Runtime.exec"
```

Real Example: CommonsCollections1

The CommonsCollections1 Gadget Chain



The Gadget Chain Explained

Step 1: Deserialize malicious `AnnotationInvocationHandler`

Step 2: `readObject()` iterates over `memberValues` (a `LazyMap`)

Step 3: `LazyMap.get()` calls `factory.transform()` on missing keys

Step 4: `ChainedTransformer` chains multiple transformations

Step 5: `InvokerTransformer` uses reflection to call methods

Step 6: Chain leads to `Runtime.getRuntime().exec()`

CodeQL Query for CommonsCollections1

```
import java
import semmle.code.java.dataflow.TaintTracking

class CommonsCollectionsGadget extends
TaintTracking::Configuration {
  CommonsCollectionsGadget() { this =
"CommonsCollectionsGadget" }

  override predicate isSource(DataFlow::Node source) {
    exists(Method m |
      m.hasName("readObject") and
```

```
      m.getDeclaringType().hasQualifiedName("java.io",

"ObjectInputStream") and
      source.asParameter() = m.getAParameter()
    )
  }
  override predicate isSink(DataFlow::Node sink) {
    exists(MethodAccess ma |
      ma.getMethod().hasName("exec") and
      ma.getMethod().getDeclaringType()
        .hasQualifiedName("java.lang", "Runtime") and
      sink.asExpr() = ma.getAnArgument()
    )
```

```
  }

  override predicate isAdditionalTaintStep(
    DataFlow::Node node1, DataFlow::Node node2
  ) {
    // Track through InvokerTransformer.transform()
    exists(MethodAccess ma |
      ma.getMethod().hasName("transform") and
      node1.asExpr() = ma.getQualifier() and
      node2.asExpr() = ma
    )
  }
}
```

Practical Workflow

Complete Analysis Workflow

1. Reconnaissance

- Identify Java applications in scope
- Check dependencies (pom.xml, build.gradle)

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2. Database Creation

```
codeql database create app-db --language=java \
  --command="mvn clean compile"
```

Complete Analysis Workflow

1. Reconnaissance

- Identify Java applications in scope
- Check dependencies (pom.xml, build.gradle)

2. Database Creation

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3. Query Selection

- Run QLinspector for gadget discovery
- Custom queries for specific patterns

Complete Analysis Workflow

4. Analysis

```
codeql database analyze app-db \
  codeql/java-queries:Security \
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```

5. Validation

- Review identified paths
- Check if gadget chain is exploitable

Learning Resources

Official CodeQL Resources

Documentation & Guides:

- CodeQL Documentation - Comprehensive reference
- CodeQL for Java - Java-specific guide
- Data Flow Analysis - Taint tracking guide

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Learning Series:

- Zero to Hero Part 1 - Fundamentals
- Zero to Hero Part 2 - Getting started
- Zero to Hero Part 3 - Security research

Java Deserialization Resources

Essential Reading:

- Synacktiv: Finding Gadgets Part 1 & 2 - Deep dive into gadget discovery
- Synacktiv: Finding Gadgets 2022 - Modern techniques
- ysoserial - Essential payload generator tool

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Tutorials & Guides:

- PortSwigger Web Security Academy - Interactive learning
- Understanding Gadget Chains - Beginner-friendly

Advanced Resources

Research & Tools:

- QLinspector - CodeQL queries for gadget finding
- GitHub Security Lab Research - Real vulnerability findings
- Java Deserialization Cheat Sheet - Comprehensive catalog

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Community Resources:

- Awesome CodeQL - Curated resource list
- CodeQL Zero to Hero Exercises - Hands-on challenges

Conclusion

Key Takeaways

1. Deserialization is Critical

- CVSS scores typically 9.0+
- Wide attack surface in enterprise Java
- Affects many popular frameworks

2. CodeQL Enables Automation

- Scales to millions of lines of code
- Finds complex gadget chains automatically
- Low false positive rate with proper queries

Questions?

Thank you for your attention!

Resources:

- GitHub: github/codeql
- QLinspector: synacktiv/QLinspector
- ysoserial: frohoff/ysoserial

Happy Hunting! 🔍