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Software testing system for detecting code injection vulnerabilities

Abstract

Systems and methods are disclosed for detecting code injection vulnerabilities in software systems. In embodiments, an injection string is created to implement an exploit against a software system. The exploit includes an unauthorized executable code that will generate an easily detectable token if executed by the software system. The string is injected into the software system during execution to simulate a code injection attack on the software system. The software system's execution result is obtained and analyzed to determine whether the execution detection token was generated. If so, the software system is proven to be vulnerable to the attack, and the vulnerability may be indicated in an alert or a report. The vulnerability detection technique may be for both software under development as well as production software systems running in the wild to analyze and monitor these systems for code injection vulnerabilities.

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Background/Summary

BACKGROUND

(1) Modern corporate software systems are continuously evolving. In such systems, software components such as software libraries can be updated, upgraded, replaced, added, and/or removed on a regular basis. The systems are run by operators of various sophistication, sometimes in cloud infrastructure provider networks with unknown adherence to security policies. Inevitably, vulnerabilities such as code injection vulnerabilities can be introduced and even re-introduced into

these systems without detection.

(2) Existing run-time security testing methods such as dynamic application testing apply an outside-in approach to finding vulnerabilities. One problem with such approaches is that they do not penetrate deeply into the software system. The external interfaces of the system provide only limited access into the system internals and existing vulnerabilities may not be reached or exposed in responses. As a result, code injection vulnerabilities introduced by new software components can go undetected despite software testing, creating security risks for the software operator.

SUMMARY OF EMBODIMENTS

(3) The systems and methods described herein may be employed in various combinations and in embodiments to perform code injection vulnerability detection for software systems. In some embodiments, the vulnerability detection system generates an injection string that contains an exploit. The exploit executes an unauthorized code to generate an execution detection token or EDT. The string is injected into the software system during execution to simulate a code injection attack on the software system. Subsequently, the software system's execution results are obtained by the vulnerability detection system and analyzed to determine whether the execution detection token was generated. If the token was generated, the software system is proven to be vulnerable to the exploit, and an alert or vulnerability report may be generated. Depending on the embodiment, the code injection vulnerability detection technique may be used to analyze software during development testing or production software systems running in the wild to analyze and monitor these systems for code injection vulnerabilities.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIG. 1 is a block diagram illustrating a code injection vulnerability detection system capable of identifying code injection vulnerabilities in a software system by injecting a string into the software system that is executable to produce an execution detection token (EDT), according to some embodiments.

(2) FIG. 2 illustrates examples of different injection strings that may be generated by the code injection vulnerability detection system, according to some embodiments.

(3) FIG. 3A illustrates use of the code injection vulnerability detection system as part of an automated software testing system, according to some embodiments.

(4) FIG. 3B illustrates use of the code injection vulnerability detection system as part of a vulnerability scanning service for scanning third party services, according to some embodiments.

(5) FIG. 4 illustrates an example implementation of the code injection vulnerability detection system that operates within a network monitoring service for monitoring client networks, according to some embodiments.

(6) FIG. 5 illustrates operations of the code injection vulnerability detection system where generated EDTs cause software systems to access an execution detection service, according to some embodiments.

(7) FIG. 6 illustrates configuration parameters and execution data collection capabilities of the code injection vulnerability detection system, according to some embodiments.

(8) FIG. 7 is a flowchart that describes an example process performed by the code injection vulnerability detection system to detect code injection vulnerabilities, according to some embodiments.

(9) FIG. 8 is a block diagram illustrating an example computer system that can be used to implement one or more portions of the code injection vulnerability detection system, according to some embodiments.

(10) While embodiments are described herein by way of example for several embodiments and

illustrative drawings, those skilled in the art will recognize that embodiments are not limited to the embodiments or drawings described. It should be understood, that the drawings and detailed description thereto are not intended to limit embodiments to the particular form disclosed, but on the contrary, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope as defined by the appended claims. As used throughout this application, the word “may” is used in a permissive sense (i.e., meaning having the potential to), rather than the mandatory sense (i.e., meaning must). Similarly, the words “include,” “including,” and “includes” mean including, but not limited to.

DETAILED DESCRIPTION OF EMBODIMENTS

(11) Various techniques are described herein to implement a code injection vulnerability detection system for software systems. The disclosed vulnerability detection system overcomes limitations of prior software testing systems to enable in-depth analysis of internal behaviors of the software system (e.g., internal API calls or data creation). Embodiments the vulnerability detection system inserts a specially generated string containing an embedded exploit that, if successfully executed, exposes a type of code injection vulnerability in the software. The exploit may be injected deeply into the software system to enable observation of internal execution behavior of the software, such as internal API calls, internal database changes, execution memory states, and the like.

(12) When the exploit code is executed, the code generates an identifier (e.g. a witness mark or execution detection token) that proves the embedded code was in fact executed by the internals of the software. In some embodiments, the code may be prepended with a header (e.g. an HTML tag) that triggers code execution in vulnerable systems. In some embodiments, the code may specify a text transformation that causes a portion of the injection string to be transformed. For instance, a publishing system may be tested with the injection string “Article big\$ {upper:b}ear”. The string “\$ {upper:b}” exposes a known vulnerability of a popular Java logging library (log4j), which will cause the string to be logged as: 2023-04-15 11:12:38 Submitted article “Article bigBear”

In contrast, a logging library that does not have the Log4Shell vulnerability will not transform the string and log the string as: 2023-04-15 11:12:38 Submitted article “Article \${upper:b}igBear”

(13) After the injection, the software system is monitored for presence of the execution detection token (here “bigBear”). If the EDT “bigBear” is detected, vulnerability to the exploit is confirmed, and an alert or report may be generated. The vulnerability detection system may monitor multiple facets of the software system, including the system's execution logs, internal databases, APIs responses, or even runtime memory. The monitoring may be performed automatically and continuously, for example, as part of an ongoing network scanning or automated software testing process. In some embodiments, the EDT may be specially formatted and/or sufficiently unique so that the vulnerability can be detected without risk of false positives. In some embodiments, to maximize the likelihood of finding a vulnerability, the detection system will inject strings repeatedly, which can be generated randomly based on a set of configuration rules.

(14) In contrast with the ephemeral and superficial testing performed by current dynamic scanners, embodiments of the disclosed vulnerability detection system allow detection tests to be performed deeply throughout the software system to surface vulnerabilities as part of the system's internally generated data. In some embodiments, poisonous data (e.g. injection strings containing the exploit) can be persisted in the software system for an extended period of time. In this manner, the software system can be tested continuously based on a single injection, even as internal components of the system change over time. In some embodiments, an exploit can be injected through a third-party system (in local as well as external environments) to further enhance the penetrative power of the detection.

(15) The described approach significantly extends the reach and coverage of vulnerability detection methods implemented by current systems. The generation of the injection strings can be controlled via configuration interfaces to reduce the amount of noise and false positives generated by the detection system. In some embodiments, the EDT may be a unique value that can be tied back to a

particular test run or test case, so that vulnerability detection reports can be generated with relevant test metadata. In some embodiments, the entire injection and detection process may be programmatically automated and orchestrated to reduce the amount of human effort and computing resources needed for the process. The described approach is highly flexible and can be employed in a variety of detection contexts, including development testing, network monitoring, penetration testing, threat hunting, third party vulnerability scanning, among others.

(16) The disclosed vulnerability detection system improves the functioning of current computer systems that implement vulnerability detection to overcome technical challenges faced by these systems. In one respect, the disclosed system reduces the amount of human effort and compute resources needed to monitor software systems for code injection vulnerabilities and allows users to easily control and manage the detection process. In another respect, the disclosed vulnerability detection system can penetrate more deeply into software systems to observe internal execution behaviors, in contrast with current vulnerability scanners that only superficially analyze responses produced by public interfaces of services. In another respect, the disclosed vulnerability detection system is able to identify novel types of exploits that are not publicly known or recorded in public vulnerability libraries. In yet another respect, the disclosed vulnerability detection system is easy to use and can be automated or reused for many different types of software systems, in contrast with penetration test tools that are largely human-driven and require expert technical knowledge.

(17) As will be appreciated by those skilled in the art, the disclosed features represent practical applications that provide real-world benefits in real-world compute systems and processes, and are not intended to capture bare mental processes, pure mathematical concepts or formula, methods of organizing human activity, fundamental economic practices, or other types of abstract subject matter not eligible for patenting. These and other features and benefits of the vulnerability detection system are described in further detail below in connection with the figures.

(18) FIG. 1 is a block diagram illustrating a code injection vulnerability detection system that is capable of identifying code injection vulnerabilities in a software system by injecting a string into the software system that is executable to produce an execution detection token (EDT), according to some embodiments.

(19) As shown, FIG. 1 depicts a code injection vulnerability detection system **110** that analyzes a software system **150** for code injection vulnerabilities. The software system **150** may be software under development or production software running in a production environment (e.g. a live web service accessible via the Internet). Depending on the embodiment, the vulnerability detection system **110** may be implemented as a part of a software testing system that tests software during development, a software monitoring or scanning service that scans production services, or a tool included in a tool suite for penetration testing or threat hunting.

(20) As shown, the code injection vulnerability detection system **110** implements a code injection string generation component **120**. Generator **120** is tasked with generating injection strings **122** to implement an exploit. The injection string **122** will be generated to include executable code that when executed produces an execution detection token (EDT) **124**. Detection of the EDT **124** from the execution results of the software system **150** indicates that the software system is vulnerable to the exploit. In some embodiments, the generation behavior of the generator **120** is configurable via a configuration interface. The generator **120** may be used to generate injection strings repeatedly and randomly according to the configuration information.

(21) In some embodiments, the generated injection strings and their associated EDTs **126** may be stored in a data store **126** of the detection system **110**, so that they can be used by the string injection component **130** during the injection phase. The EDTs may be stored along with the injection records so that they can be matched to the execution results of the software system during the detection phase. The EDTs may be individually unique, and in some embodiments, uniquely identify the particular injection attempt, injection campaign, test run, or test case of the detection system. When the string injector **130** injects a stored injection string, it may at that time generate an

injection record in the data store **126**. The injection record may include metadata about the injection, such as the time of injection, the manner of injection, the type of exploit implemented by the injection, and any tester comments. This metadata information can be linked back to detection results if a vulnerability is later detected.

(22) The string injector **130** is responsible for injecting **132** the strings into the software system **150**. Depending on the embodiment, the injector **132** may be accomplished in a variety of ways. For offline systems (e.g. software that is under development), the string injection may have more latitude to inject strings that can cause harmful impacts on the software system **150**. Offline systems are typically run in a testing environment to process synthetic data (e.g. in staging environment) or on production data with no external influence (e.g. canary systems). However, they are typically isolated from external clients so that any harmful impacts of the execution cannot affect clients. This isolation enables software testers to inject exploits into the systems without real business side-effects, leading to a very thorough vulnerability assessment of internal systems. It is especially useful as a part of a development cycle, alongside integration and acceptance tests.

(23) Online systems typically run in production environments on production data. With online systems, testers cannot generally perform testing in a way that crashes the system or harms the system's clients. Moreover, testers may be limited in terms of the number and types of interfaces that are available for injection. However, in some cases, injection can be accomplished through a different software system **160**, as shown. As one example, if the software system **150** relies on data from a third-party directory service, attack strings may be injected into the system **150** by adding directory entries to the directory service that contain the strings. In some cases, this technique may also be used to detect or assess the vulnerabilities of the other software system **160**.

(24) In some embodiments, the injection **132** may be performed as part of an automated testing process, such as ongoing regression testing, unit testing, integration testing, etc. In some embodiments, the injection **132** may be performed by a vulnerability scanner or penetration test platform, on a production service. As shown, injection strings may be submitted through a variety of injection avenues, such as the interfaces of external-facing components **152** (e.g. the public request interface of a web service), internal interfaces of internal components **156** (e.g. a library API), and internal data stores **158** (e.g. an internal database or configuration file). In some embodiments, the injection **132** may be performed via another software system **160** that provides data to the software system **150**.

(25) In some embodiments, opportunistic string injection may be used to extend data in a database randomly or semi-randomly. For example, the string may be injected as a user comment of an existing user of the system. In some embodiments, the string injection may add a field in one or more API calls or database statements. Synthetic string injection into an internal database may require some knowledge of the database object model. The injection **132** may cause artificial data objects to be created in the database (e.g. artificial users or products) with executable code embedded in certain fields (e.g. a user's or product's name). The processing of these fields may cause the exploit to be executed by the software system. Injecting strings into a database to create artificial data is a technique that can be used for online systems, since the artificial data can be made separate and distinguishable from real business data and is not typically processed together with real business data. Moreover, because the injected string can be persisted in the database indefinitely, the string can be left in place for future vulnerability detections as the software system changes.

(26) As shown, once an injection string **122** is injected, it may cause unintended code executions within various parts of the software system **150** to create instances of the EDT **124a-d**. As shown, the EDT **124d** may also be generated in a downstream software system **170** that receives data from the injected software system **150**. Thus, in some cases, an injection **132** may reveal vulnerabilities in a web of related software systems that propagate data among one another.

(27) As shown, the generated EDTs **124a-d** may be embedded in execution results **142**, which are

provided back to the code injection vulnerability detection system **110**. These execution results **142** are analyzed by the code execution detection component **140** to look for the presence of EDTs **124**. If instances of the EDT are found in the execution results, the code injection vulnerability detection system **110** has determined that the software **150** is vulnerable to the exploit.

(28) As with the string injection **132**, the execution results **142** may be obtained from a variety of different facets of the software system **150**. In some embodiments, the code execution detector **140** may scan or monitor an internal database (e.g. data store **158**) for instances of EDTs **124**. If the detector **140** has access to the database, it may perform online scans of the data using a query language such as SQL, or alternatively examine database backups or dumps.

(29) In some embodiments, logs of the software system **150** may be accessible. One common type of logs are web logs produced by web servers. These logs can contain intermediate information produced by execution of the software, which may include instances of EDTs. As a specific example, the Log4Shell vulnerability (CVE-2021-44228) is a type of vulnerability that can be observed in logs generated by certain versions of the Log4j Java logging framework.

(30) In some embodiments, the code execution detector **140** may be able to obtain the contents of volatile memory of the software system **150** during execution, which can indicate instantiations of EDTs in memory. The memory state of the software **150** may be collected by the execution environment (e.g. a virtual machine manager or container manager that can snapshot or scan the memory of guest virtual machines or containers), an agent process running alongside the software process, or via code instrumentation within the software system. In some embodiments, the memory state of the software system may be dumped to a persistent data store at certain checkpoints, and these dumps can be provided to the code execution detector **140**.

(31) In some embodiments, API requests or responses associated with internal API calls may contain EDTs **124**. The API may be the primary interface between in-house and third-party components within the software system, or between in-house components in microservice-based systems. In some embodiments, a first API request may inject the attack string, and a second API call may be used to extract the EDT. For example, the first API call may be an HTTP PUT request that injects the string, and the second API call may be an HTTP GET request that retrieves the string. Use of third-party APIs for vulnerability detection may be limited based on their potential business side effects on the third-party service. For example, an email provider service may require external testers to use valid email addresses, while allowing exploits to be included in the body of the email, in order to avoid undesired disruptions to the service. Example types of API data that can be monitored for the EDT detection include HTML pages returned by web servers, JSON/HTML documents required by web services, query results of database services, and responses from software-as-a-service (SaaS) APIs.

(32) In some embodiments, the code execution detector **140** may be run independently from the string injector **130** to continuously watch for the presence of EDTs produced by the software system **150** and match them to the injection records. The code execution detector **140** may be configured to watch for EDTs in the execution results of many different software systems **150**, produced by injection strings injected by many different injectors **130**. In some embodiments, the code execution detection component may determine from the execution results **142** that the software system is not vulnerable to a type of exploit. For example, the detector **140** may make such a determination if the EDT is not observed after a specified period of time, or if a specific “non-execution” detection token is observed that proves the exploit was not successfully executed within the software system.

(33) In some embodiments, if a vulnerability is detected by the code execution detector **140**, the system **110** will issue an alert (e.g. a user alert to an administrator) or generate a report (e.g. a system vulnerability report) indicating the vulnerability. In some embodiments, the system **110** may automatically perform certain remediation actions in response to a detected vulnerability. Such actions may include initiating more intensive testing to probe for details about the vulnerability, or

isolating or quarantining the software system from sensitive data or other systems.

(34) FIG. 2 illustrates examples of different injection strings that may be generated by the code injection vulnerability detection system, according to some embodiments.

(35) As shown, the figure depicts three example injection strings **210**, **220**, and **230**. Injection string **210** illustrates a string that includes executable code **214** to transform a portion of the string **210**. In this example, the executable code is demarcated in the surrounding non-executable data **212** by a prefix **216** and a suffix **218**, which will cause vulnerable systems to invoke an “upper” function to convert the letter “b” to uppercase “B”. Note that while in this example the executable code **214** is embedded in non-executable data **212a** and **212b**, in other cases, the surrounding data **212** can be another type of code that can be interpreted or executed, such as SQL, HTML, or a URL.

(36) The prefix may be a combination of characters that breaks the flow of the surrounding data or code and enables the code **214** to be executed. For example, the prefix may include delimiters specially crafted for programming languages used in the system. Common examples of characters that break code flow in coding languages include quotes, double quotes, commas, and special tag sequences such as “<?php”. In some cases, the prefix may be empty.

(37) The suffix may be a combination of characters that terminates the code **214** within the string and enables code to be executable. For example, the “?>” suffix terminates a segment of PHP code in an HTML document. In some cases, the suffix may be empty.

(38) The code is a sequence of characters that may be executed if the data is incorrectly handled in the system or if it is manipulated by vulnerable software. Preferably, code is crafted in a way that does not disturb the vulnerable system. In some embodiments, the code **214** may invoke one or more function calls to perform a transformation whose result is unique and easily detectable.

(39) In injection string **210**, the code **214** will transform the string to “BigBear” in vulnerable systems where the code can be executed. The term “BigBear” is the EDT and indicates a successful execution of the exploit. Systems that do not perform this unauthorized execution will not produce the EDT. Injection string **210** can be used to detect the Log4Shell vulnerability, where the logging library will interpret the {\$upper:} syntax.

(40) The precise formatting of the injection string will depend on the type of software system and the exploit being simulated. The executable code **214** may be specified in a programming language specific to the type of exploit. Common languages that may be used for the code **214** include Java, JavaScript, Hypertext Preprocessor (PHP), and Structured Query Language (SQL). In some embodiments, the selection of programming language(s) used for the code is configurable by the user as a configuration parameter.

(41) Injection string **220** provides another example of an injected string. In this example, a PHP code statement **222** is enclosed in HTML preprocessor tags so that it can be embedded in an HTML document and executed by a vulnerable system. The code **222** causes an PHP interpreter to compute the MD5 hash of a string, which is preferably unique and may be randomly generated. The output of the code **222** is included in the HTML output so that it can be easily observed.

(42) The code **222** may use a variety of functions to generate the EDT. For example, the query string “select md5 (‘id-xyz’)” may be used to simulate a SQL injection attack with similar results as the PHP example. A JavaScript code segment may invoke the JavaScript library function Math.log(12345) to compute the natural logarithm of float number, which is preferably unique and can be randomly generated. In a JavaScript environment, the results of a computation can be printed via the console.log() function or added to the parent document with document.createTextNode() and document.body.appendChild(). In some embodiments, the choice of functions invoked in the code is configurable by the user.

(43) Injection string **230** provides another example of an injected string. In this example, a JavaScript code segment is enclosed in HTML tags to write a value to the parent HTML document. As shown, the value written by the write function includes an escape sequence that translates to an escaped character **232** (here the exclamation character). In some embodiments, this escaping can be

performed in order to improve penetration of the exploit. To improve code penetration, certain special characters are escaped so that they pass superficial checks by the software system to sanitize input strings for invalid characters. For example, if the software system sanitizes a particular data field to remove instances of the exclamation character, the escape sequence **232** in injection string **230** will allow the injected string to avoid the sanitation. The escaped character may be corrected de-escaped by the software system later in the processing. Character escaping is language-dependent, and the injector **130** may use variations of character escapes for common programming languages to maximize the chances of code penetration. Commonly escaped characters include ' , " , < , > , ? , % , & , \ , and / . A common method of escaping is by using the \ prefix or ASCII encoding with % prefix. In some embodiments, the manner in which character escaping is performed in injection strings is configurable by the user.

(44) FIG. 3A illustrates use of the code injection vulnerability detection system **110** as part of an automated software testing system **310**, according to some embodiments.

(45) As shown in this example, the software testing system **310** is configured to inject **132** test strings into the software system **320** and receive execution results **142** from the software system. The software testing system **310** may be configured to perform testing on software that is currently under development, or on a production software system that is running in a live production environment. The testing system **310** may perform tests on the software in an automated fashion, for example, regularly according to a set schedule or in response to specified events. In some embodiments, the string injection and vulnerability detection functionality of the testing system may be implemented as one of multiple testing tools integrated into the testing system.

(46) As shown, in some embodiments, the functioning of the software testing system **310** may be controlled by test configuration data **312**. Such configuration data may specify how testing is performed on the software **320**. The configuration data may specify information such as test case definitions and test run schedules or conditions. Additionally, the configuration data may specify parameters that are specific to the string injection behavior of the system. These parameters may include injection string controls that specify how strings are to be generated. For example, injection string control parameters may specify a selection of programming languages to use for the executable code used in the injection strings, a selection of functions to execute by the executable code, a length of the string, a format of the string, or a set of characters to use in the string, among other things.

(47) In some embodiments, the configuration data **312** may specify how injections are to be injected into the software and EDTs are to be detected from the software. As discussed, the string injections **132** and execution result collection **142** may be performed via multiple different avenues, which can be controlled by the user via testing configuration. For example, during development testing when the testing system has access to various internal components of the software, the configuration may specify particular internal APIs of specific system components **322** and **324** to use for the injection, and a particular internal log **326** of the system to use for collecting execution results. Internal system components that may be tested may include internal system work or message queues, databases, indexes, library modules, etc. In some embodiments, the testing may also use execution artifacts for injection or detection, including temporary files, runtime memory snapshots, host machine registries, etc.

(48) As shown, in this example, the testing system **310** extracts certain testing results **314** from the execution results **142**. The testing results may be specific to a particular test case or test run and include an identifier of the individual test run or test case. For a code injection test, the testing result may indicate the exploit type that was being targeted by a particular injection, and EDT detection metadata associated with the injection. The detection metadata may indicate whether the EDT was detected or not, and when and where the EDT was detected. In some embodiments, the testing results **314** may also include execution metadata about the actual execution that generated the EDT, which may be captured by the executable code embedded in the string. Such information

may include the time when the code was executed, one or more environment variables of the execution environment that executed the code, a component identifier of the component that executed the unauthorized code, and/or call stack data (e.g. a call stack trace) associated with execution of the code.

(49) FIG. 3B illustrates use of the code injection vulnerability detection system **110** as part of a vulnerability scanning service **330** for scanning third party services, according to some embodiments.

(50) As shown in this example, a vulnerability scanning service **330** is configured to scan third-party services **340a-c** for code injection vulnerabilities using the code injection vulnerability detection system **110** of FIG. 1. In some embodiments, the third-party services **340** may be web-based services or simple HTTP web servers that are publicly accessible via a public network such as the Internet. In some embodiments, the vulnerability scanning service **330** may be a private service that is configured to scan services with a private network. The scanning service **330** may be configured to monitor the services **340** for vulnerabilities by repeatedly performing vulnerability scans on the services.

(51) As shown, in some embodiments, the scanning performed by the service **330** may be controlled by scanning configuration data **334**. The configuration data may specify operational parameters of the scanning, such as scan targets, scan schedules, what types of exploits to include in a scan, and any alert configurations that control how alerts are generated if vulnerabilities are detected in a scan. For example, in some embodiments, a detected vulnerability may be reported in real time via a text or email message to a subscribing user, such as an administrator of a service **340**. In some embodiments, the alert may be generated via a graphical user interface of an incident detection and response (IDR) service provider that is responsible for monitoring the third-party services **340**.

(52) In some embodiments, some of the scanning configuration **334** of the scanning service **330** may be derived from a vulnerability database **332**. Such a database may contain a library of publicly known vulnerabilities of software systems, including code injection vulnerabilities. The scanning service **330** may be configured to scan for known vulnerabilities listed in the database **332**. In some embodiments, the injection strings generated by the scanning service may be created according to generation rules specified in the vulnerability database. For example, the vulnerability database **332** may include information about the Log4Shell vulnerability, and specify rules to generate testing strings to target that vulnerability (e.g. using the logging library's particular syntax).

(53) In some embodiments, the scanning service **330** may be implemented to include (or as part of) a penetration testing platform **338**. Such a testing platform may allow software testers to perform customized penetration testing or threat hunting on the services **340**. These users may specify scanning configurations **334** to perform ad hoc scanning of the services **340** to inject specific attack strings into the services and monitor the services for generated EDTs.

(54) As shown, embodiments of the scanning service **330** are able to extract scanning results **336** from the execution of the services **340** after the attack strings are injected. The scanning results **336** may include a scan ID that ties a scan result to a particular scan. In some embodiments, the scan ID may be a reference ID that is generated along with or as part of the EDT. In some embodiments, the reference ID may be obtained by the operator of the third party service **340** (e.g. using a tool provided to the third party operator), and reference ID allows the operator to access scanning records maintained by the scanning service **330** and receive instructions regarding remediation steps to address the detected vulnerability. In some embodiments, the scanning results **326** may include demographic or statistical information that is aggregated from many third party services **340** monitored by the scanning service **330**. Such information may indicate, for example, the types of vulnerabilities that are observed globally on the Internet, the prevalence of different types of vulnerabilities, and various time trends associated with different types of vulnerabilities.

(55) FIG. 4 illustrates an example implementation of the code injection vulnerability detection system that operates within a network monitoring service **430** for monitoring client network(s) **410**, according to some embodiments.

(56) As shown, an instance of the code injection vulnerability detection system **110** is implemented in a network monitoring service **430**. In some embodiments, the network monitoring service **430** may be a service implemented in the cloud and on a service provider network, such as a platform-as-a-service (PaaS) network, an infrastructure-as-a-service provider (IaaS) network, or a software-as-a-service (SaaS) network. The network monitoring service **430** may be configured to communicate with many agents **416a-d** deployed on machines **414a-d** in a client network **410**. The agents **414** may communicate with the network monitoring service **430** over one or more intermediary networks **420**. In some embodiments, the agents may be configured to collect or compile network activity data or events **425**, and transmit the data to the network monitoring service **430**. The network monitoring service **430** may receive network activity data from many different client networks operated by different entities, companies, organizations, groups, etc., and perform remote monitoring of the networks of these different clients. The network monitoring service **430** may analyze the network events **425** to monitor the client network **410** for security incidents or security posture problems.

(57) In some embodiments, the collected network events **425** may include the execution results **142** of software in the client network **410** and may include or indicate EDTs **124** generated during executions of the software. Depending on the embodiment, the agents **416** may be controllable by the network monitoring service **430** to perform string injections **132**, collect execution results **142**, detect software vulnerabilities, or a combination of these tasks.

(58) As shown, the client network **410** in this example includes different types of computing resources, such as a workstation **414a**, a server **414b**, a mobile device **414c**, and a virtual machine **414d**. The virtual machine **414d** may be an instance of a computer and operating system that is emulated and hosted on a physical virtual machine host. The virtual machine host may implement virtualization hardware and/or software (e.g. a hypervisor) to execute and manage multiple instances of guest operating systems. Example implementations of such virtualization technologies include VMWARE ESX/ESXI, MICROSOFT HYPERV, ORACLE VIRTUALBOX, QEMU, and Kernel-based Virtual Machine (KVM). Another type of virtualized execution environment may be a hosted container, which provides a portable and isolated execution environment over a host operating system of a physical host. Examples of container hosting technologies include DOCKER and GOOGLE KUBERNETES. In some embodiments, the virtual machine **414d** may be hosted in a platform service provider network, such as the platform service provider network that is hosting the network monitoring service **430**. Depending on the embodiment, the agents **416** may be deployed on other types of computing systems, including embedded systems, networking devices, storage devices, Internet-of-Things (IoT) devices, vehicles, and the like.

(59) In various embodiments, the network **420** may encompass any suitable combination of networking hardware and protocols necessary to enable communications between the agents **416** and the network monitoring service **430**. In some embodiments, the remote machines **414** may execute in a private network of a company, behind a company firewall, and the network **420** may include a public network such as the Internet, which lies outside the firewall. The network **420** may encompass the different telecommunications networks and service providers that collectively implement the Internet. In some embodiments, the network **420** may also include private networks such as private local area networks (LANs), private wide area networks (WANs), or private wireless networks. The network **420** may be implemented using different hardware (e.g., modems, routers, switches, load balancers, proxy servers, etc.) and software (e.g., protocol stacks, routing software, firewall/security software, etc.) for establishing networking links between the remote machines **414** and the network monitoring service **430**. In some embodiments, the agents **416** may transmit the network events **425** to the network monitoring service **430** over secure communication

channels such as transport layer security (TLS) connections implemented over the network **420**.

(60) As shown in this example, the network monitoring service **430** is implemented using a number of supporting services **440**, **450**, and **470** implemented by the service provider network. Clients of the network monitoring service **430** may convey service requests to and receive responses from these services via their respective service interfaces. In some embodiments, the service request and responses may be defined as part of a RESTful API (e.g. one or more web services). The requests and responses may be formatted as JSON documents. In some embodiments, the network monitoring service **430** may implement service interfaces using other types of remote procedure calling protocols, such as GOOGLE PROTOCOL BUFFERS. The platform service provider network may provide the hardware and/or software needed to implement service endpoints for these services, and the request routing facilities to ensure that a request is properly routed to the appropriate endpoints.

(61) As shown, the service provider network may provide different types of service provider resources **490**, which can be leased by customers to implement hosted services. As shown, the platform service provider may provide resource services such as compute resource service **492**, storage resource service **494**, networking resources service **496**, orchestration service **498**, and resource metrics service **499**. The services of the network monitoring service **430** may be built using these underlying resource services provided by the platform service provider. In some embodiments, the platform service provider resources **490** may implement features such as load balancing of service requests and/or dynamic management and scaling of service node pools. In some embodiments, each of the services **440**, **450**, and **470** may be implemented using a pool of service nodes provided by the platform service provider, which may be individual instances of virtual machines. In some embodiments, the platform service provider may be a provider such as AMAZON WEB SERVICES or MICROSOFT AZURE.

(62) In some embodiments, the network monitoring service **430** may be configured to monitor, analyze, and take action on security-related incidents that are detected in the remote client networks **410**. In some embodiments, the network monitoring service **430** may implement an event logging service **430** that receives network events **425** from the remote client network and stores the received data as event logs data **460**. The event logging service **440** may implement service functionality to allow users or other software components to query the event logs **460**. As shown in this example, the log data **460** may be analyzed by the execution detection component **140** to monitor for the presence of EDTs **124**. The vulnerability detection system **110** may execute continuously on incoming log data **460** to watch for any EDTs **124** produced by strings injected by the injector component **130** and report any detected code injection vulnerabilities to downstream assessment services **470** and/or an alert interface **454** implemented as part of a user interface **450**.

(63) As shown, in some embodiments, the assessment service(s) **470** may implement a variety of monitoring processes to generate alerts in response to detected security problems in the client network **410**. These alerts may be forwarded to the alert interface **454**, which will allow human security analysts to perform a more in-depth examination of the underlying security problems. For example, in some embodiments, a malware detection module **472** may examine collected machine event logs to detect installation of a particular type of malware executable. As another example, an attack detection module **474** may examine the email event logs to detect phishing attacks using new or unusual email addresses, web addresses, or email content. As yet another example, a policy violation detection module **476** may examine the configuration changes in the client network **410** to detect violations of security policies. In some embodiments, the alerts generated by the assessment service(s) **470** may trigger automated mitigation or remediation actions to be performed on the client network **410** to address detected threats in the client network, for example, to gather additional data about the threats from the client network, or quarantine or isolate components of the client network from sensitive data or other components.

(64) As shown, in some embodiments, the network monitoring service **430** may implement one or

more user interface(s) **450**, which may be implemented as GUIs or web interfaces viewable using a web browser. In some embodiments, these user interfaces **450** may be implemented by client-side applications. As shown, the user interfaces may include the alert interface **454** to notify users of detected alerts. In some embodiments, the alert interface **454** may be accessible from both the client network **410** and a central monitoring location where security analysts are monitoring the client network.

(65) In some embodiments, the user interface(s) **450** may also implement a configuration interface **452**. The configuration interface **452** may be used to configure various aspects of the network monitoring system **230**, including the vulnerability detection system **110**. For example, the configuration interface **452** may be used to specify the testing configurations **312** or scanning configurations **324**, as discussed in connection with FIGS. 3A and 3B.

(66) FIG. 5 illustrates operations of the code injection vulnerability detection system where generated EDTs cause software systems to access an execution detection service, according to some embodiments.

(67) As shown, in some embodiments, the injection strings generated by the string injector **130** produce unique addresses or access tokens directed to an external execution detection service **540**, and cause the software systems **510**, **520**, and **530** to perform an access of the execution detection service **540**. For example, the generated EDT may be a specific URL **512** that refers to a monitored resource. The URL may refer to an image located at http://example.com/unique_id.jpeg. The URL may be generated with embedded code that will only recreate the URL if an exploit is successfully executed by the software system **510**. Thus, if the software system later accesses the monitored resource at the execution detection service **540** associated with the URL, a vulnerability to the exploit has been demonstrated. As shown, in some embodiments, the execution detection service **540** may track service access records **542** from many software systems **510**, **520**, and **530**, and provide the records to the code execution detection component **140** for further analysis and/or reporting.

(68) Depending on the embodiment, different types of EDTs can be used to produce observable side effects from the software. For example, instead of a URL **512**, the generated EDT may be another type of address such as an IP address, an email address **522**, or a directory address **532**. For example, a software system that has the Log4Shell vulnerability will successfully interpret the string “\${jndi:ldap://example.com/unique\${e3z1:-e}_id}” to cause an access a resource associated with the directory address.

(69) FIG. 6 illustrates configuration parameters and execution data collection capabilities of the code injection vulnerability detection system, according to some embodiments.

(70) As discussed, in some embodiments, the injection string generator **120** may generate injection strings randomly. However, this random generation may be tuned, constrained, or controlled by string generation configurations **610**. This configuration may be specified as part of testing configuration data **312**, scanning configuration data **334**, or rules stored in a vulnerability database **332**, as discussed previously. As shown, depending on the type of exploit, the string generation configuration data **610** may limit the random string generation to a selection of programming languages to use for the executable code, a selection of functions to be invoked by the code (preferably “pure” functions that produce deterministic output given the same input and with no side effects), a specific length or format of the injection string, and/or a specific set of characters of the injection string (or special characters to be escaped).

(71) In some embodiments, the string generation configuration data **610** may also specify additional execution context data **630** that are to be obtained along with the EDT. Such execution context data may be collected by including additional executable code as part of the exploit. Depending on the embodiment, the execution context data **630** may be collected via the same injection string that generates the EDT or a sequence of multiple injection strings sent as part of a progressive probing of the software. The execution context data **630** may be encoded as part of the

EDT, or stored as a separate data structure that can be accessed separately (e.g. in an execution log that can be accessed to retrieve the execution results **142**). As shown, example types of execution context data **630** that may be collected by string injections **132** include the execution time of the executable code, various execution environment variables (e.g. the launching parameters of a Java virtual machine), the identity of the execution component that executed the code (e.g. the provider and version of a library component), the execution call stack, and/or other aspects of the execution memory state at the time of execution. In some embodiments, the collected execution context data **630** may be reported along with the detected vulnerability in the detection alert or vulnerability report.

(72) FIG. 7 is a flowchart that describes an example process performed by the code injection vulnerability detection system **110** to detect code injection vulnerabilities, according to some embodiments.

(73) The process begins at operation **710**, where the injection string **122** is generated. The injection string contains an exploit that includes an unauthorized executable code that, when executed, generates an execution detection token or EDT **124**. The unauthorized code is used to simulate a code injection attack on a software system. In some embodiments, the executable code is a code that exploits a vulnerability of the software system, and cannot be executed without the vulnerability. The software system may be a variety of software including software under development or production software running in production environments, including publicly accessible services on the Internet. The generation of the string may be performed repeatedly and randomly as a part of a monitoring process, and may be controlled by string generation configuration specifications on rules. In some embodiments, the injection strings are generated according to a type of exploit being targeted, and the generation rules may be specified as part of a vulnerability database.

(74) At operation **720**, the string is injected into an execution of the software system to simulate a code injection attack on the software system. The injection may occur via many different facts of the software system, including an API of the software system (including public request API or internal component APIs), a database of the software system, a configuration file or repository of the software system, a library component used by the software system, or another software system that provides data to the software system. The injection may be recorded in a data store along with the expected EDT that will be produced by the injected string, so that the EDT can be used to scan execution results of the software system during the detection phase.

(75) At operation **730**, the system obtains an execution result of the software system after the injection of the string. The execution result of the software system may be obtained from different avenues, including an API response of the software system, a log of the software system, a database of the software system, a volatile memory of the software system, or another software system that receives data from the software system. As discussed in connection with FIG. 5, in some embodiments, the execution result may be a side effect produced by the injection string, for example, an attempt by the software system to access an external service using a particular service address generated as a result of the injected exploit.

(76) At operation **740**, the system determines whether the execution result indicates that the EDT was generated during the execution of the software system. For example, the execution results may be scanned or monitored for the generated EDT. As another example, the fact that the EDT was generated may be detected based on an outbound access of the software system. A determination that the EDT was generated proves that the exploit was successfully executed within the software system. The EDT may be sufficiently unique so that detections have no risk of false positives. In some embodiments, the system may affirmatively determine from the execution results that the EDT was not generated by the software system. If the EDT is not generated, the process may loop back to repeat the monitoring process.

(77) If the EDT was generated, the process proceeds to operation **750**, where an indication is output

that the software is vulnerable to the type of exploit or code injection attack that was performed. In some embodiments, the indication may be output as an alert, which may be broadcast to subscribing users or displayed on a graphical user interface (e.g. the GUI of an incident detection and response (IDR) center). In some embodiments, the indication may be added to a vulnerability report of the software system, which may be provided to software testers or owner/operators of the software system that have subscribed to a vulnerability scanning service. In some embodiments, detection of the vulnerability may trigger certain automated events on the software system, such as rejection of a change to the software system, performance of more targeted testing on the software system, or isolating or quarantining the software system from other production environment systems.

(78) FIG. 8 is a block diagram illustrating an example computer system that can be used to implement one or more portions of the code injection vulnerability detection system, according to some embodiments. For example, the computer system **1000** may be a server that implements one or more components of the code injection vulnerability detection system **110** of FIG. 1. In some embodiments, the computer system **1000** may be used to implement one or more components of the network monitoring service **430** of FIG. 4.

(79) Computer system **1000** may be implemented using a variety of computing devices, such as a personal computer system, desktop computer, laptop or notebook computer, mainframe computer system, handheld computer, workstation, network computer, a consumer device, application server, mobile telephone, or some other type of computing device.

(80) As shown, computer system **1000** includes one or more processors **1010**, which may include multiple cores coupled to a system memory **1020** via an input/output (I/O) interface **1030**. Computer system **1000** further includes a network interface **1040** coupled to I/O interface **1030**. In some embodiments, computer system **1000** may be a uniprocessor system including one processor **1010**, or a multiprocessor system including several processors **1010a-n**, as shown. The processors **1010** may be any suitable processors capable of executing instructions. For example, in various embodiments, processors **1010** may implement one of a number of instruction set architectures (ISAs), such as the x86, PowerPC, SPARC, or MIPS ISA.

(81) As shown, the computer system **1000** may also include one or more network communication devices (e.g., network interface **1040**) for communicating with other systems and/or components over a communications network. For example, an instance of an application executing on computer system **1000** may use network interface **1040** to communicate with another server application executing on another computer system, as described herein.

(82) As shown, computer system **1000** may use its network interface **1040** to communicate with one or more other devices **1060**, such as persistent storage devices and/or one or more I/O devices. In some embodiments, some of these other devices may be implemented locally on the computer system **1000**, accessible via the I/O interface **1030**. In various embodiments, persistent storage devices may include disk drives, tape drives, solid state memory, other mass storage devices, or any other persistent storage device. The computer system **1000** may store instructions and/or data in persistent storage devices, and retrieve the stored instruction and/or data as needed.

(83) As shown, the computer system **1000** may include one or more system memories **1020** that store instructions and data accessible by processor(s) **1010**. In various embodiments, system memories **1020** may be implemented using any suitable memory technology, (e.g., one or more of cache, static random-access memory (SRAM), DRAM, RDRAM, EDO RAM, DDR 10 RAM, synchronous dynamic RAM (SDRAM), EEPROM, non-volatile/Flash-type memory, etc.). The system memory **1020** may be used to store code **1025** or executable instructions to implement the methods and techniques described herein. For example, the executable instructions may include instructions to implement the code injection vulnerability detection system **110**, as discussed. The system memory **1020** may also be used to store data **1026** needed or produced by the executable instructions. For example, the in-memory data **1026** may be used to store the injection strings **122**,

as discussed.

(84) In some embodiments, some of the code **1025** or executable instructions may be persistently stored on the computer system **1000** and may have been loaded from external storage media. The persistent storage of the computer system **1000** and the external media are examples of non-transitory computer-readable storage media, which may be used to store program instructions to be executed by the computer system **1000**. A non-transitory computer-readable storage medium may provide the capability to store information in a form readable by a machine (e.g., computer system **1000**). Non-transitory computer-readable media may include storage media such as magnetic or optical media, disk or DVD/CD-ROM devices, archival tapes, network-attached storage systems, or other computer systems.

(85) In some embodiments, the I/O interface **1030** may be configured to coordinate I/O traffic between processor **1010**, system memory **1020** and any peripheral devices in the system, including through network interface **1040** or other peripheral interfaces. In some embodiments, I/O interface **1030** may perform any necessary protocol, timing or other data transformations to convert data signals from one component (e.g., system memory **1020**) into a format suitable for use by another component (e.g., processor **1010**). In some embodiments, I/O interface **1030** may include support for devices attached through various types of peripheral buses, such as a variant of the Peripheral Component Interconnect (PCI) bus standard or the Universal Serial Bus (USB) standard, for example. In some embodiments, the function of I/O interface **1030** may be split into two or more separate components, such as a north bridge and a south bridge, for example. Also, in some embodiments, some or all of the functionality of I/O interface **1030**, such as an interface to system memory **1020**, may be incorporated directly into processor **1010**.

(86) In some embodiments, the network interface **1040** may allow data to be exchanged between computer system **1000** and other devices attached to a network. The network interface **1040** may also allow communication between computer system **1000** and various I/O devices and/or remote storage systems. Input/output devices may, in some embodiments, include one or more display terminals, keyboards, keypads, touchpads, scanning devices, voice or optical recognition devices, or any other devices suitable for entering or retrieving data by one or more computer systems **1000**. Multiple input/output devices may be present in computer system **1000** or may be distributed on various nodes of a distributed system that includes computer system **1000**. In some embodiments, similar input/output devices may be separate from computer system **1000** and may interact with one or more nodes of a distributed system that includes computer system **1000** through a wired or wireless connection, such as over network interface **1050**. Network interface **1040** may commonly support one or more wireless networking protocols (e.g., Wi-Fi/IEEE 802.11, or another wireless networking standard). In some embodiments, the network interface **1040** may support communication via telecommunications/telephony networks such as analog voice networks or digital fiber communications networks, via storage area networks such as Fibre Channel SANs, or via any other suitable type of network and/or protocol.

(87) Although the embodiments above have been described in considerable detail, numerous variations and modifications may become apparent to those skilled in the art once the disclosed inventive concepts are fully appreciated. It is intended that the following claims be interpreted to embrace all such variations and modifications, and the above description to be regarded in an illustrative rather than a restrictive sense.

Claims

1. A system, comprising: one or more computing devices configured to implement a software testing system, configured to: generate a string that contains an exploit, wherein the exploit includes executable code that, if executed by a software system, causes an execution detection token (EDT) to be generated, wherein the EDT contains a unique value that indicates vulnerability

of the software application to the exploit with no risk of false positives; store the EDT in a data store of the software testing system as part of an injection record; inject the string into an execution of the software system to simulate a code injection attack on the software system; obtain an execution result of the software system after the injection of the string; match the execution result to the injection record in the data store to detect that the EDT was generated during the execution; and output an indication that the software system is vulnerable to the exploit based on the detection that the EDT was generated.

2. The system of claim 1, wherein the software testing system is configured to: inject another string that contains the exploit into an execution of another version of the software system; obtain another execution result of the other version of the software system after the injection of the other string; determine, based on the other execution result, that the other version of the software system is not vulnerable to the exploit; and output an indication that the other version of the software system is not vulnerable to the exploit.

3. The system of claim 1, wherein the executable code is demarcated within the string by a prefix or suffix.

4. The system of claim 1, wherein the software testing system is configured to: generate strings randomly and inject the strings into executions of the software system as part of an automated testing of the software system, wherein the randomization constrained by user specification that specifies one or more of: a selection of programming languages to use for the executable code, a selection of functions to execute by the executable code, a length of the string, a format of the string, or a set of characters to use in the string.

5. The system of claim 1, wherein the software testing system is configured to perform testing on the software system during development of the software system.

6. The system of claim 1, wherein the software testing system is configured to perform testing on a production version of the software system.

7. The system of claim 1, wherein: the software system sanitizes input data by removing one or more of a set of special characters from the input data; and the software testing system is configured to escape the one or more special characters in the injected string so that the one or more special characters are not removed by the software system.

8. The system of claim 1, wherein to inject the string into the software system, the software testing system is configured to: submit the string via a request interface of the software system; submit the string via an internal interface implemented by an internal component of the software system; add the string to a database of the software system; add the string to a configuration file of the software system; add the string to a library component loaded by the software system; or inject the string into another software system that provides data to the software system.

9. The system of claim 1, wherein to detect that the EDT was generated, the software testing system is configured to detect the EDT: in a response generated by the software system, in a log of the software system, in a database of the software system, in a volatile memory image of the software system, or in data of another software system that receives data from the software system.

10. The system of claim 1, wherein: the EDT includes a service address of a network service; and to detect that the EDT was generated, the software testing system is configured to detect an access of the network service via the service address.

11. The system of claim 1, wherein: the software system is implemented at web server; and the string is injected via a Hypertext Transfer Protocol (HTTP) request to the web server; and the EDT is detected in a log of the web server.

12. The system of claim 1, wherein the executable code includes one or more of Java code, JavaScript code, Hypertext Preprocessor (PHP) code, or Structured Query Language (SQL) code.

13. The system of claim 1, wherein the executable code executes a pure function on at least a portion of the string.

14. The system of claim 1, wherein the executable code performs a transformation on at least a

portion of the string.

15. The system of claim 1, wherein execution of the executable code causes additional testing data to be generated along with the EDT, including one or more of: a time when the executable code was executed, one or more variables of an execution environment that executed the executable code, or a component identifier of a component of the software system that executed the executable code.

16. The system of claim 1, wherein the software testing system is configured to generate different types of injection strings to test for different types of exploits stored in a library, and the different types of strings are generated according to generation rules stored in the library.

17. A method, comprising: performing, by a software testing system implemented by one or more computing devices: generating a string that contains an exploit, wherein the exploit includes executable code that, if executed by a software system, causes an execution detection token (EDT) to be generated, wherein the EDT contains a unique value that indicates vulnerability of the software application to the exploit with no risk of false positives; storing the EDT in a data store of the software testing system as part of an injection record; injecting the string into an execution of the software system to simulate a code injection attack on the software system; obtaining an execution result of the software system after the injection of the string; matching the execution result to the injection record in the data store to detect that the EDT was generated during the execution; and outputting an indication that the software system is vulnerable to the exploit based on the detection that the EDT was generated.

18. The method of claim 17, wherein the method is performed as part of development testing on the software system during development of the software system.

19. The method of claim 17, wherein the method is performed production testing on a production version of the software system.

20. The method of claim 17, wherein detecting that the EDT was generated comprises detecting the EDT: in a response generated by the software system, in a log of the software system, in a database of the software system, in a volatile memory image of the software system, or in data of another software system that receives data from the software system.
