A Formal Approach to Exploiting Multi-Stage Attacks based on File-System Vulnerabilities of Web Applications
(Extended Version)

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Abstract. Web applications require access to the file-system for many different tasks. When analyzing the security of a web application, security analysts should thus consider the impact that file-system operations have on the security of the whole application. Moreover, the analysis should take into consideration how file-system vulnerabilities might interact with other vulnerabilities leading an attacker to breach into the web application. In this paper, we first propose a classification of file-system vulnerabilities, and then, based on this classification, we present a formal approach that allows one to exploit file-system vulnerabilities. We give a formal representation of web applications, databases and file-systems, and show how to reason about file-system vulnerabilities. We also show how to combine file-system vulnerabilities and SQL-Injection vulnerabilities for the identification of complex, multi-stage attacks. We have developed an automatic tool that implements our approach and we show its efficiency by discussing several real-world case studies, which are witness to the fact that our tool can generate, and exploit, complex attacks that, to the best of our knowledge, no other state-of-the-art-tool for the security of web applications can find.

1 Introduction

Context and motivations. Every month a large number of novel web applications (web apps, for short) are launched that provide useful functionalities to administer bank accounts, manage personal health records, sell and buy goods, and so on. These functionalities regularly attract more users... and attackers! Hand-in-hand with the increase of web apps available and features provided, there has been an exponential increase in the number of web applications breached to expose private and sensitive data, with companies and users realizing they were victims of an attack often only months after it occurred \cite{21,22,23}. Modern web applications often make intensive use of functionalities for reading and writing content from the web app’s file-system (i.e., the file-system of the web server that hosts the web app). Reading from and writing to the file-system are routine operations that web apps perform for different tasks. For instance, the option
of dynamically loading resources based on runtime needs is commonly adopted by developers to structure the web app’s source code for stronger reusability. Similarly, several web apps allow users to upload (write) content that can be shared with other users or can be available from a web browser as in a cloud service. Reading and writing functionalities are offered by most server-side programming languages for developing web apps such as PHP [28], JSP [20] or ASP [4]. Modern database APIs also provide a convenient way to interact with the file-system (e.g., backup or restore functionalities), but they also increase the attack surface an attacker could exploit. Whenever an attacker finds a way to exploit vulnerabilities that allow him to gain access to the web app’s file-system, the security of the whole web app is put at high risk. Indeed, both OWASP [27] and MITRE [8] list vulnerabilities that compromise the file-system among the most common and dangerous vulnerabilities that afflict the security of modern software.

Vulnerability assessment and penetration testing are the two main steps that security analysts typically undertake when assessing the security of a web app and other computer systems [7,16,31]. During a vulnerability assessment, automatic scanning tools are used to search for common vulnerabilities of the system under analysis (Wfuzz [36] and DotDotPwn [13] are the main tools for file-system-related vulnerabilities). However, it is well known [14] that state-of-the-art scanners do not detect vulnerabilities linked to the logical flaws of web apps. This means that even if a vulnerability is found, no tool can link it to logical flaws leading to the violation of a security property. The result of the vulnerability assessment is thus used to perform the second and more complicated step: during a penetration test (pentest), the analyst defines an attack goal and manually attempts to exploit the discovered vulnerabilities to determine whether the attack goal he defined can actually be achieved. A pentest is meant to show the real damage on a specific web app resulting from the exploitation of one or more vulnerabilities. Consider the following example, which is simple but also fundamental to understand the motivation for the approach that we propose.

Trustwave SpiderLabs found a SQL injection vulnerability in Joomla! [19], a popular Content Management System (CMS). In [33], Trustwave researchers show two things: the code vulnerable to SQL injection and how the injection could have been exploited for obtaining full administrative access. The description of the vulnerable code clearly highlights an inadequate filtering of data when executing a SQL query. The description of the damage resulting from the exploitation of the SQL injection shows that an attacker might be able to perform a session hijacking by stealing session values stored as plain-text in the database. The result of this analysis points out two problems: Joomla! is failing in (1) properly filtering data used when performing a SQL query and (2) securely storing session values. Problem (1) could have been identified by vulnerability scanners

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[3] The Top 10 compiled by OWASP is a general classification and it does not include a specific category named “file-system vulnerability”; however, “Injections”, “Broken Authentication and session Management”, “Security misconfiguration” (just to name a few) can all lead to a vulnerability related to the file-system.
(e.g., sqlmap is able to identify the vulnerability), but no automatic vulnerability scanner can identify Problem (2) and only a manual pentesting session is effective. However, manual pentesting relies on the security analyst’s expertise and skills, making the entire pentesting phase easily prone to errors. An analyst might underestimate the impact of a certain vulnerability leaving the entire web app exposed to attackers. This is why we can’t stop at the identification of a SQL injection or file-system-related vulnerability, and why we can’t address the ensuing attacks with a manual analysis. Our approach addresses this by automating the identification of attacks that exploit such multi-stage vulnerabilities.

**Contributions** Our contributions are two-fold. First, we formally define file-system vulnerabilities and how to exploit them to violate security properties of web apps. A number of formal approaches based on the Dolev-Yao (DY) attacker model [12] have been developed for the security analysis of web apps, e.g., [13,14,15,16,17]. However, file-system vulnerabilities of web apps have never been taken into consideration by formal approaches before. In this paper, we define how web apps interact with the file-system and show how the DY model can be used to exploit file-system vulnerabilities. Moreover, we extend our previous work on the exploitation of SQL-Injection (SQLi) vulnerabilities [10] by showing how to combine file-system vulnerabilities and SQLi vulnerabilities for the identification of complex, multi-stage attacks commonly identified only by manual analysis during the pentesting phase. It is crucial to point out that we do not search for payloads that can be used to exploit a particular vulnerability, but rather we exploit file-system vulnerabilities.

Second, to show that our formalization can effectively generate multi-stage attacks where file-system and SQLi vulnerabilities are exploited, we have developed a prototype tool called WAFEx (Web Application Formal Exploiter, [11]) and we discuss here its application to four real-world case studies. WAFEx can generate, and exploit, complex attacks that, to the best of our knowledge, no other state-of-the-art tool for the security analysis of web apps can find. In particular, we show how WAFEx can automatically generate different attack traces violating the same security property, a result that only a manual analysis performed by a pentester can achieve. In each attack trace, multiple vulnerabilities (e.g., file-system and SQLi) are used in combination.

**Organization** In §2 we give a classification of file-system vulnerabilities and describe the advantages an attacker gains in exploiting such vulnerabilities. In §3 we provide our formalization. In §4, we describe the WAFEx tool and discuss its application to complex real-world case studies. We discuss related work in §5, and we provide conclusions and discuss future work in §6. The appendices contain full details on our formal specifications and case studies.

### 2 A classification of file-system-related vulnerabilities

To provide a coherent and uniform starting point for reasoning about file-system-related vulnerabilities, in this section we give a classification of the vulnerabilities
of web apps that lead to compromise the file-system. The two security properties 
that we consider in our formalization are:

- **Authentication bypass**: the attacker gets unauthorized access to a restricted 
  area.
- **Confidentiality**: the attacker gets access to the content stored in the web 
  app’s file-system that is not meant to be publicly available.

We have identified five vulnerability categories, which we describe below, focusing 
on the main details of the attacks that are relevant for our formalization.

1. **Directory Traversal (DT) (a.k.a. Path Traversal)** Operations on files 
   (reading and writing) performed by a web app are intended to occur in the 
   root directory of the web app, a restricted directory where the web app actually 
   resides. A DT vulnerability refers to a lack of authorization controls when an 
   attacker attempts to access a location that is intended to identify a file or directory 
   stored in a restricted area outside the web app’s root directory. Whenever 
   the access permissions of a web app are not restricted in such a way that they 
   only allow users to access authorized files, an attacker might be able to craft a 
   payload that allows him to access restricted files located outside the web app’s root directory. DT payloads make use of special characters such as the double dots “..” and the forward slash “/” separator, which, when combined, allow the 
   attacker to specify arbitrary locations that can escape outside the root directory 
   of a web app. DT attacks can be further divided in Relative DT and Absolute DT, depending on whether the payload refers to a relative or an absolute path. Since a DT vulnerability refers to a lack of authorization permissions, to actually exploit it, it is necessary for an attacker to find an entry point that allows 
   him to send input to the web app that is then used to create a file-location string. This means that a DT vulnerability is always exploited in combination 
   with another vulnerability that provides such an entry point to the attacker. For 
   example, imagine that `index.php?load=file` refers to a web page `index.php` 
   that dynamically loads the file specified by the value of `load`. An attacker might 
   modify this value and use it as input vector to exploit a DT vulnerability.

2. **SQL-Injection (SQLi)** Web apps make use of a Database Management System (DBMS) in order to store data. This allows for functionalities such as 
   blog posting, forum discussions, etc. Querying a database is performed using 
   the Structured Query Language SQL and whenever a query is created using 
   user-supplied data, SQLi attacks could be possible [10,17,26]. Most modern 
   DBMSs provide APIs that extend SQL’s expressiveness by allowing SQL code 
   to access a web app’s file-system for reading and writing purposes. Reading 
   APIs allow developers to produce code that retrieves content stored in the web 
   app’s file-system and loads it in the database. This is particularly convenient 
   when a web app needs to load bulks of data into the database, e.g., as part of 
   an initialization or restoring process. Writing APIs allow developers to produce 
   code that saves content from the database to the web app’s file-system. This 
   is particularly convenient for features such as backup or upload functionalities. 
   When an attacker finds an SQLi entry point, he can inject arbitrary SQL syntax 
   that modifies the behavior of the original query. Attackers mainly exploit SQLi
to bypass authentication mechanisms or to extract data from the database, but, as there is no limit on the SQL syntax that could be injected, it is also possible to exploit reading and writing APIs to access the underlying file-system [2].

As an example, consider the MySQL DBMS [23], which has the built-in API LOAD_FILE() for reading text or binary files from the file-system [23]. To execute LOAD_FILE(), the user executing the query needs to have the FILE privileges, which give the DBMS permission to read and write files on the server. The file accessed by the attacker must be owned by the user that started MySQL or be readable by all users. Similarly, MySQL provides APIs for writing to the file-system with the SELECT ... INTO statement, which enables the result of a SELECT query to be written to a file. For instance, in presence of a UNION query-based SQLi, an attacker might inject the payload 1 UNION ALL SELECT 1,LOAD_FILE('/etc/passwd'),3,4 FROM mysql.user-- that will give him reading access to the file /etc/passwd.

(3) File Inclusion (FI) All programming languages for the development of web apps support functionalities for structuring code into separate files so that the same code can be reused at runtime by dynamically including files whenever required. A FI vulnerability refers to a lack of proper sanitization of user-supplied data during the creation of a file location string that will be used to locate a resource meant to be included in a web page. When the file location depends on user-supplied data, an attacker can exploit it and force the inclusion of files different from the ones intended by the developers. FI might allow an attacker to access arbitrary resources stored on the file-system and to execute code. FI attacks can be further divided in Local FI and Remote FI, which force the inclusion of files stored locally or remotely, respectively.

As an example, consider the PHP code in Listing 1.1. Line (2) gets a user-supplied parameter \$_GET['user'] and stores it into the variable $username that is then used to create a file location (3), which is in turn used to include a resource in the current page (4). If, as the user's value, an attacker injects the payload .htaccess, he might access the .htaccess file, which allows one to make configuration changes on a per-directory basis [2].

Listing 1.1: PHP code vulnerable to FI.

1 $username = \$_GET['user'];
2 $filepathname = "/var/www/html/".$username;
3 include $filepathname;

FI can be combined with the DT vulnerability, allowing an attacker to gain access to resources stored on the web app's file-system but outside the web app's root folder. Consider again Listing 1.1 and suppose that the web server hosting the web app is a unix server. The attacker might then inject a malicious payload such as ../.../.../etc/passwd, where /etc/passwd is the common location pointing to a text-based database listing the users of the system. Assuming that the root directory of the web app is located at /var/www/html/site/, the PHP code will try to include the file /var/www/html/site/.../.../etc/passwd,
and the path is translated into `/etc/passwd`, forcing the web app to include the file and thus giving the attacker access to the list of users for the web server.

(4) **Forced Browsing (FB)** (a.k.a. Direct Request) refers to a lack of authorization controls when a resource is directly accessed via URLs. This lack of authorization might allow an attacker to enumerate and access resources that are not referenced by the web app (thus not directly displayed to the users through the web app) or that are intended to be accessed only as a result of previous HTTP requests. By making an appropriate HTTP request, an attacker could access resources with a direct request rather than by following the intended path. The lack of authorization controls comes from the erroneous assumption that resources can only be reached through a given navigation path. This mis-assumption leads developers to implementing authorization mechanisms only at certain points along the way for accessing a resource, leaving no controls when a resource is directly accessed.

As an example, consider a web app where the URL `http://vuln.com/admin/index.php` points to the login page and `http://vuln.com/admin/admin.php` points to the administration page accessible once the login has succeeded. When FB is possible, an attacker might be able to directly access the administration page by requesting the URL `http://vuln.com/admin/admin.php` without first logging in. If the `admin.php` page does not verify whether the request is made by an authorized user, the attacker has skipped the login process provided by `http://vuln.com/admin/index.php`.

Another example is a development environment that is supposed to be accessible only by developers. Developers usually erroneously assume that since the development environment is not directly accessible from the main website, users have no means to access this area, so an attacker might try to guess the name of the development environment (e.g., `http://vuln.com/dev/`) and increase the chance of having unauthorized access to the web app.

(5) **Unrestricted File Upload (UFU)** A widespread feature provided by web apps is the possibility of uploading files that will be stored on the web app’s file-system. An UFU vulnerability refers to a lack of proper file sanitization when a web app allows for uploading files. The consequences can vary, ranging from complete takeover with remote arbitrary code execution to simple defacement, where the attacker is able to modify the content shown to users by the web app.

As an example, consider a web app that allows users to upload images (e.g., an avatar to customize the user profile). [Listing 1.2](#listing1.2) gives the HTML code of the file upload form, [Listing 1.3](#listing1.3) gives the PHP code that performs the upload but without carrying out any control over the file being uploaded, paving the way to UFU attacks.

Listing 1.2: HTML code that shows a file upload form.

```html
<form enctype="multipart/form-data" action="uploader.php" method="POST">
    Choose a file to upload: <input name="uploadedfile" type="file" /><br />
    <input type="submit" value="Upload File" />
</form>
```
Listing 1.3: PHP code for uploading a file.

1. $path = "uploads/";
2. // where the file will be saved
3. $target_path = $target_path . basename($_FILES['uploadedfile']['name']);
4. // move uploaded file from tmp directory to target path
5. if (move_uploaded_file($_FILES['uploadedfile']['tmp_name'], $target_path)) {
6.   echo "file " . basename($_FILES['uploadedfile']['name']) . " uploaded!";
7. } else { echo "there was an error uploading the file"; }

UFU can also be used in combination with DT, allowing the attacker to overwrite arbitrary files stored in the web server. However, modern web app programming languages (like PHP) perform a sanitization on the uploaded file path string by removing any special characters such as ".." and "/" used to change the current path, making the exploitation of a DT less likely to happen.

3 A formalization to reason about file-system vulnerabilities

We will now describe how we formally represent the behavior of a file-system and of a web app that interacts with it. We also show how our formalization allows the DY attacker to successfully exploit file-system vulnerabilities. In our formalization, we used ASLan++, the formal specification language of the AVANTSSAR Platform [3], but in fact our approach is general and for the sake of readability we give here pseudo-code rather than ASLan++. (see the appendix for the full ASLan++ code).

Our approach doesn’t search for payloads that can be used to exploit file-system vulnerabilities, but rather analyzes the security of web apps by exploiting vulnerabilities that lead attackers to have unauthorized access to the file-system. To deal with such vulnerabilities, we need to represent the behavior of the
(i) web app, which defines the interaction with the client, the file-system and the database,
(ii) file-system, which interacts with the web app and the database for reading and writing content,
(iii) database, which can also interact with the file-system,
(iv) attacker, who interacts only with the web app.

We do not formalize the behavior of honest clients since we assume the DY attacker to be the only agent to communicate with the web app, i.e., we are only interested in dishonest interactions. This is because the exploitation of file-system vulnerabilities doesn’t require interaction with the honest users.

To explain how our formalization works, we will use a simple FI example depicted in Fig. 1 as a Message Sequence Chart (MSC) in which there are three entities: client, web app and file-system (the fourth entity, database, does not send messages and will be discussed later). In this example and, in general, in
Fig. 1: MSC of a FI vulnerability.

In our formalization, we assume the web app and the file-system (and the database) to have a long-lasting secure relation, i.e., no attacker can read or modify the communication between them. Moreover, as is standard, constants begin with a lower case character (e.g., `filePath`), variables with an upper case one (e.g., `Page`).

In step (1), the client sends to the web app a message containing the variable `Page`, representing the page to be included. In step (2), the web app performs a read operation by issuing a `read(Page)` request. In step (3), the file-system checks if the requested page points to an existing file and, in step (4), it replies to the web app with a variable `Response` that represents the result of the read operation. In step (5), the web app forwards the response to the client.

**Definition 1.** Messages consist of variables $V$, constants $c$, concatenation $M.M$, function application $f(M)$ of uninterpreted function symbols $f$ to messages $M$, and encryption ${\{M\}}_M$ of messages with public, private or symmetric keys that are themselves messages. We define that $M_1$ is a submessage of $M_2$ as is standard (e.g., $M_1$ is a submessage of $M_1.M_3$, of $f(M_1)$ and of ${\{M_1\}}_{M_4}$) and, abusing notation, we then write $M_1 \in M_2$.

### 3.1 The DY attacker as a web attacker

The DY model [12] defines an attacker that has total control over the network but cannot break cryptography: he can intercept messages and decrypt them if he holds the corresponding keys for decryption, he can generate new messages from his knowledge and send messages under any agent name. Message generation and analysis are formalized by derivation rules, expressing how the attacker can derive messages from his knowledge in order to use them for performing attacks.

Suppose that we want to search for a FI vulnerability possibly leading the attacker to access resources stored outside the root folder of the web app (DT).

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4 We assume the communication with the file-system to be secure since the file-system actually is not a real network node, and thus no attacker can put himself between the communication with the file-system, i.e., man-in-the-middle attacks are not possible.

5 In this paper, we need not distinguish between different kinds of encrypted messages, but we could do it by following standard practice. Here we don’t even need to consider explicitly encrypted messages, but we add them for completeness.
As described in [2], the attacker can try to access resources by injecting a payload used for accessing a file that will be included in the current page. However, it is important to point out two fundamental aspects of our work: (1) as stated, we are not interested in generating the payloads that will exploit vulnerabilities, but rather we want to represent that a vulnerability can be exploited and what happens when it is exploited, and (2) we want to avoid state-space explosion by making the models as simple as possible. We have thus introduced the constant fsi that represents any and all payloads for exploiting file-system vulnerabilities (e.g., ../../../ for DT). By using fsi and the definition of the file-system entity §3.2, we allow the DY attacker to deal with file-system vulnerabilities.

3.2 File-system

We will now give a formalization of the file-system entity that can be used in any specification when searching for attacks related to file-system vulnerabilities of web apps. As depicted in Fig. 1, the file-system can be seen as a network node always actively listening for incoming connections, and the web app sends reading and writing requests to the file-system.

Our formalization aims to abstract away as many concrete details as possible, while still being able to represent the exploitation of file-system vulnerabilities, and so we do not represent the file-system structure but rather formalize messages sent and received along with reading and writing behavior. This allows us to give a compact formalization so as to avoid state-space explosion problems when carrying out the analysis with the model checker.

Incoming messages

As incoming messages for the file-system entity, we consider only reading and writing requests, for which we use the uninterpreted functions readFile() and writeFile(), both taking a generic variable Filepath that represents a file location in the file-system.

Reading and writing behavior

To exploit vulnerabilities related to reading and writing operations, we need to represent the available files in addition to the behavior of the two operations. We represent the existence of a file by means of the predicate inFS(), i.e., inFS(filePath) means that the file represented by the constant filePath is stored in the file-system.

When the file-system entity receives a reading request readFile(filePath), it checks, by means of inFS(), whether the file exists: if so, then it answers to the request with file(filePath), i.e., wrapping the file being read with the uninterpreted function file(), else the constant no_file is returned [7].

When the file-system entity receives a writing request writeFile(file), it uses inFS() to mark the file as part of the file-system but it need not return a result to the web app (as explained in Footnote 6).

To represent an attacker’s attempt to access files, we include the Horn clause

\[ \text{fs_hc_evil}(M): \text{inFS}(\text{fsi}.M) \]

[7] We don’t need to consider access control policies/models as they are external to the web app. Hence, we assume that every file that is in the file-system can always be read and that every writing operation will always succeed.
that states that the predicate inFS() holds for a message whenever it is of the form fsi_M, i.e., a message that is a concatenation including the constant fsi that represents a payload to exploit file-system vulnerabilities. More specifically, this states that the attacker has injected a malicious payload fsi into the parameters (expressed as a variable) M. In case of a DT attack, one may think of fsi as the ...././ payload that escapes from the web app’s root folder.

**The specification** Summarizing, the pseudo-code representing the file-system behavior is in Listing 1.4 (the full ASLan++ specification is in §D). We represent the file-system as a network node always actively listening for incoming messages. More specifically, we define the file-system by two mutually exclusive branches of an if-elseif statement: in the guard in line (1) the file-system receives (expressed in Alice&Bob notation) a reading request and in (4) it receives a writing request. For the reading request, the file-system verifies the existence of the file (2): if the file exists, then the file-system returns the variable Filepath wrapped with the uninterpreted function file() (2), else the constant no_file is returned instead (3, where ! formalizes negation). As we assume that writing operations always succeed, when a writing request is received, the file-system marks the new file as “existing” by means of inFS() and need not return (4).

Listing 1.4: Pseudo-code representing the behavior of the file-system; we write FS for the file-system and Entity as a general entity (either web app or database).

```plaintext
1 if( Entity -> FS: readFile(Filepath)) {
2     if( inFS(Filepath)) {
3         FS -> Entity : file(Filepath);
4     } elseif( !( inFS(Filepath))) {
5         FS -> Entity : no_file;
6     } elseif( Entity -> FS: writeFile(Filepath)) {
7         inFS(Filepath);
8     }
```

3.3 Database

To cover all file-system vulnerabilities (§2), we need to formalize a database that can interact with the file-system. We can adapt the basic formalization we gave in [10] for the case of SQLi vulnerabilities by including interaction with the file-system (and thus to also be able to cover file-system access through SQLi vulnerabilities, see §2). We can see the database, like the file-system, as a network node that interacts with the web app and the file-system. The idea behind the extension is to make the database able to perform a reading or writing request to the file-system whenever a query is valid. We also modified how sanitized queries are handled by removing the sanitization function sanitizedQuery() from the database specification of [10] and introducing a new uninterpreted function sanitized() that represents a general sanitization function (see §3.4 for further details). For brevity, we give in §A a description of the database behavior as given in [10] while in this section we focus on the extension.
The pseudo-code of the extension is shown in Listing 1.5. The database entity is still represented by an if-elseif statement. The main if branch (1) handles sanitized queries, represented with the new sanitization function, whereas the second branch (3) handles raw queries. Within the raw query branch, we have defined two additional behaviors. The first new branch performs a read operation on the file-system (5) and, if the file-system sends back a file (6), the database wraps the answer from the file-system with \texttt{tuple()} and sends it back to the web app (6). The second new branch (7) handles writing operations performed by the database, for which the answer to the web app will be a message of the form \texttt{tuple(newFile(filePath))}, where \texttt{newFile()} is an uninterpreted function stating that a file has been written as a result of a SQL query.

```
1 if(WebApp -> DB: query(sanitized(SQLquery))){
2     if(SQLquery == tuple(*)){
3         DB -> WebApp: no_tuple;
4     } else if(WebApp -> DB: query(SQLquery)){
5         if(inDB(sqlquery)){
6             DB -> WebApp: tuple(SQLquery);
7         } else if(inDB(SQLquery)){
8             DB -> FS: read(SQLquery);
9             if(FS -> DB: file(SQLquery)){
10                DB -> WebApp: tuple(file(SQLquery));
11            } else if(inDB(SQLquery)){
12                DB -> FS: write(SQLquery);
13            } else if(!(inDB(SQLquery))){
14                DB -> WebApp: tuple(new_file(SQLquery));
15            } else if(!(inDB(SQLquery))){
16                DB -> WebApp: no_tuple;
17            }
18        }
```

3.4 Web application

The web app is another node of the network that can send and receive messages. In our formalization, the web app can communicate with client, file-system and database. In [10] we also provided some guidelines on how to represent web apps, however, they were limited to basic interaction with the database. In this paper we provide extended guidelines that also take the file-system into consideration.

The file-system and the database entities don’t depend on the web app and thus we can reuse them in every model. The web app formalization does depend on the scenario being modeled, but we give a series of guidelines on how to represent the web app’s behavior for testing the interaction with the file-system and the database.

\textbf{If statements} HTTP is a stateless protocol, which means that each pair request-response is considered as an independent transaction that is not related to any previous request-response. We use if statements to define that a web app can answer different requests without following a specific sequence of messages, thus representing the stateless nature of HTTP. The web app’s model is thus a sequence of if statements defining all the requests the web app can handle.
Client communication A general HTTP request (and response) header comprises different fields that are needed for the message to be processed by the browser. In our formalization, we don’t need to represent all the fields of a real request (or response) header as they are not relevant to the analysis, and thus we limit to: a variable representing the sender, a variable representing the receiver, and a concatenation of constants and variables representing the message.

In case of a request, the message would be represented by the HTTP query string containing parameters and values. For example, a request to the URL http://example.com/index.php?page=menu.php can be represented as `Client -> WebApp : index.Page`, where `index` is a constant representing a web page and `Page` is a variable representing an HTTP query value. We proceed similarly to formalize a response from the web app to the client. We only represent the details needed for the analysis:

- a constant representing the returned page (e.g., dashboard, admin etc),
- the function `file()` when the web app performs a reading operation on the file-system, and
- the function `tuple()` that, following [10], is returned only if the executed query is SELECT, UPDATE or DELETE.

For example, the response `WebApp -> Client : dashboard.file(fsi)` can be used to represent the result of a successful request where the client receives the dashboard page. The message `file(fsi)` is returned to express that a file was retrieved from the file-system.

File-system and database communication As already stated in §3.2, whenever the web app has to read content from the file-system, it sends a `readFile()` request and whenever it has to write to the file-system, it sends a `writeFile()` request. When the web app has to perform a SQL query on the database, it sends a `query()` request to the database (see §3.3). To allow the web app to represent sanitized input, we introduced an uninterpreted function `sanitized()` that allows the modeler to “switch on” or “switch off” the possibility of exploiting a vulnerability either of the file-system or of the database, letting the model-checker analyze the web app for possible attacks. The web app has to check the response coming from the file-system or the database in order to behave properly. For example, if a file is being read, the web app has to check that the file-system is answering with the uninterpreted function `file()` before proceeding further.

Remote code execution Our formalization can represent scenarios where the attacker is able to write arbitrary files into the web app’s file-system leading to arbitrary remote code execution. As described earlier, a web app model is a sequence of if statements defining the requests the web app responds to. The possibility of uploading a file that leads to code execution can be seen as a way of increasing the number of requests the web app responds to. We then include into the model of the web app a series of predefined if branches representing the behavior of common malicious code an attacker might try to upload. We define that these malicious if branches can be used by the attacker only if the file exists.
in the file-system (i.e., inFS() is valid for that file). This will ensure that the attacker finds a way of writing the malicious file before actually using it.

**Sessions** As already mentioned, HTTP is a stateless protocol. In order for the user to experience a stateful interaction with a web app (e.g., the web app recognizes when a user is logged-in when he changes page), developers make use of sessions. A session allows a web app to store information into a memory area in order to have it accessible across multiple pages. When a request is made to a web page that creates a session, the web page allocates a memory area and assigns to that area a session identifier. The same session identifier is sent back to the client (generally as a cookie value) within the response for that request. When a cookie is received, a web browser automatically sends it back to the web app when a new request is made. The web app receives the session identifier and uses it to retrieve the information stored within the associated memory area.

In order to represent sessions, we introduced the predicate sessionValue() to state that a variable is a session value. Whenever a request is made to a page that creates a session value, a new variable is created, marked as a session value and returned to the client. Whenever a page requires a session prior to performing any further step, the page needs to verify that one of the variables sent to the web app is indeed a session value.

**Taking stock** Listing 1.6 can now finally formalize the FI example of Fig. 1. The web app accepts a request for include.Page, where include is a constant representing the web page being requested and Page is a variable representing the page to include (1). The web app sends a reading request with the page received by the client (1). The file-system checks if the file is stored in the file-system and then sends a response to the web app (2): if the response is of the form file(Page) (3), then the web app sends back to the client include (representing an included web page) along with file(Page) (representing the content of the included file), else it sends include without further details (4).

Listing 1.6: Pseudo-code representing the behavior of FI example of Fig. 1

```plaintext
1 if( Client -> WebApp : include.Page ){  
2     WebApp -> FS : read(Page);  
3     FS -> WebApp : Response;  
4     if( Response == file(Page) ){  
5         WebApp -> Client: include.file(Page);  
6     } else{  
7         WebApp -> Client : include;  
8     } 
```

### 3.5 Goals

The last component of the formalization is the goal (or security property) that should be verified. As we discussed in §2, we are not interested in finding file-system vulnerabilities but rather we want to exploit them. In particular, we define security properties related to authentication bypass and confidentiality breach, which, respectively, express that the attacker can access some part of the
web app that should be protected with some sort of authorization mechanisms, or obtain information that is “leaked” from the web app (such “leakage” can happen from either the file-system or the database).

We use the LTL “globally” operator [], which defines that a formula has to hold on the entire subsequent temporal path, and the iknowledge predicate, which represents the knowledge of the attacker. We can then represent authentication goals by stating that the attacker will never have access to some specific page, and confidentiality goals by stating that the attacker will never increase his knowledge with parts coming from the file-system or the database, i.e., file(). The confidentiality goal for the FI example in Fig. 1 is shown in Listing 1.7 stating that the attacker will never know something of the form file().

Listing 1.7: Confidentiality goal for the FI example in Fig. 1

\[](!\(\text{iknowledge}(\text{file}(*)))\)

4 Our tool WAFEx and its application to case studies

In this section, we show how our formalization can be used effectively for representing and testing attacks involving the exploit of file-system vulnerabilities. We have developed a prototype tool, called WAFEx, that shows how the abstract attack trace (AAT) generated from our models can be concretized and tested over the implementations of the real web apps. We have tested WAFEx on Damn Vulnerable Web Application (DVWA) and on Multi-Stage, a web app we wrote for security testing and freely available at [11]. DVWA is a vulnerable web app that provides an environment in which security analysts can test their skills and tools. DVWA is divided in examples implementing web pages vulnerable to the most common web app vulnerabilities. We selected three relevant exercises from DVWA: FI, UFU and SQLi. WAFEx was able to identify the intended vulnerability on all the case studies and was also able to identify an unintended vulnerability of SQLi for file reading in the SQLi exercise of DVWA.

In the remainder of this section, we will describe WAFEx and present the Multi-Stage case study that shows how file-system vulnerabilities and SQLi can be combined for the generation of multi-stage attack traces on the same web app.

Our pool of case studies might look small and trivial at first, but it is worth noting that DVWA is a state-of-the-art testing environment used for teaching the security of web apps to pentesters and the case studies represent real scenarios that might be implemented by many web apps. Moreover, ethical aspects prevented us from blindly executing WAFEx on the Internet since our implementation makes use of brute-forcing tools such as Wfuzz and sqlmap, whose unauthorized usage must be approved by the owner of the web app. Finally, we didn’t test the latest release of any free CMSs as that would require a first phase of vulnerability assessment, which is out of the scope of this work.
We give here only the pseudo-code specification of the web apps and the goals; full models in pseudo-code and ASLan++ can be found in §C and §D respectively.

4.1 WAFEx: a Web Application Formal Exploiter

WAFEx takes in input an ASLan++ specification together with a concretization file that contains information such as the real URL of the web app and the name of the real parameters used for making requests (see Fig. 2 in §B for a detailed description of the workflow of our approach and tool). We have chosen ASLan++ so to apply the model-checkers of the AVANTSSAR Platform [3] (in particular, CL-AtSe), but our approach is general and could be used with other specification languages and/or other reasoners implementing the DY attacker model.

To aid the security analyst in the model creation, we have written a Python script that allows him to first use the Burp proxy [29] to record a trace of HTTP requests/responses generated by interacting with the web app, and then use our script to convert this trace into an ASLan++ model. The analyst has to specify the behavior for the HTTP requests and the security goal he wants to test.

By using the ASLan++ translator [3], WAFEx generates a transition system that is given in input to the model-checker CL-AtSe, which generates an AAT as an MSC if an attack was found. WAFEx reads the MSC and the concretization file, and executes the AAT over the real web app. WAFEx makes use of the external tools Wfuzz [36] and sqlmap [32] in order to perform attacks. WAFEx is also able to automatically use information it extracts during an attack (e.g., as a result of FI) to proceed further with the execution of an AAT. We have run WAFEx on our case studies using a Mac Book laptop (Intel i5-4288U with 8G RAM and Python3.5). The execution time of the model-checking phase ranges from 30ms to 50ms, while the overall process (from MSC generation to concretization) depends on the external tools Wfuzz and sqlmap.

4.2 Case study: the Multi-Stage web app

Multi-Stage is a web app that we specifically wrote in order to show how file-system and SQLi vulnerabilities can be combined together to generate multiple attack traces. We designed Multi-Stage to ensure that it is realistic and representative of software that could indeed be deployed.

Multi-Stage implements a typical HTTP login phase in which users can log into the system by providing username and password. The web app performs a query to the database in order to verify the credentials and grant access to a restricted area. The restricted area allows users to view other users’ profiles and modify their own personal information (Name, Surname, Phone number), and it allows for the upload of a personal image to use as avatar. We check the web app for file reading attacks, i.e., we want to generate multi-stage attack traces showing how an attacker can exploit file-system and SQLi vulnerabilities to get read access to the web app’s file-system. A detailed description of the model can be found in §C.4 and in [11].
We ran this model with WAFEx in order to test the security of Multi-Stage. Unfortunately, the model-checker CL-AtSe that we use inside WAFEx does not allow for generating multiple attack traces (nor do the other back-ends of the AVANTSSAR Platform). Thus, whenever a trace was found, we disabled the branch corresponding to the attack and run WAFEx again to generate another trace different from the previous one. This process does, of course, miss some traces since by disabling a branch we prevent any other trace to use that branch in a different step of the attack trace. However, it shows that multiple traces can actually be generated. We generated three different AATs: #1, #2 and #3.

**AAT #1** This first AAT shows how an attacker might be able to exploit an SQLi in the login phase to directly read files from the file-system (Listing 1.8). The attacker $i$ sends to the web app a request for login by sending the payload `sqli.fsi` (1). The web app sends a query to the database entity (2), which forces the database into sending a read request to the file-system entity with value `fsi` (3). The file-system checks if the provided file is part of the file-system and answers to the database with that file (4). The database forwards the response from the file-system to the web app (5), which, finally, sends to the attacker the dashboard page along with the result from the database (6).

Listing 1.8: AAT #1 for accessing the file-system in Multi-Stage.

```
1  i -> WebApp : login.sqli.fsi.Password
2  WebApp -> DB: query(sqli.fsi)
3  DB -> FS : readFile(fsi)
4  FS -> DB : file(fsi)
5  DB -> WebApp : tuple(file(fsi))
6  WebApp -> i : dashboard.AuthCookie.tuple(file(fsi))
```

**AAT #2** We disabled the branch that allows the database to read from the file-system and ran the model again in order to generate a different AAT (Listing 1.9). The attacker $i$ tries to exploit a SQLi in order to write a malicious file so to exploit a remote code execution. $i$ sends to the web app a request for login by sending the payload `sqli.evil_file` (1). The web app sends a query to the database entity (2), which forces the database into sending a writing request with value `evil_file` to the file-system (3). The file-system marks the new file as available in the file-system and the database sends a response to the web app with the file just created (4). The web app responds to $i$ with the dashboard page along with a newly generated cookie and the result of the creation of a new file (5). The attacker $i$ now exploits the `evil_file` by sending the payload `fsi` to the web app (6). The web app will now perform a `readFile()` operation on the file-system and will send the retrieved file back to the attacker (7-9).

Listing 1.9: AAT #2 for accessing the file-system in Multi-Stage.

```
1  i -> WebApp : login.sqli.evil_file.Password
2  WebApp -> DB: query(sqli.evil_file)
3  DB -> FS : readFile(fsi)
4  FS -> DB : file(fsi)
5  DB -> WebApp : tuple(file(fsi))
6  WebApp -> i : dashboard.AuthCookie.tuple(file(fsi))
```

We plan to extend CL-AtSe or replace it with a tool capable of generating multiple attack traces.
AAT #3 We disabled the branch that allows the database to both read and write from the file-system, and ran the model again to generate a different AAT [Listing 1.10]. The attacker \(i\) bypasses the authentication mechanism by sending the sqli payload (1). This allows him to have access to the web app, which responds with a valid authentication cookie value (2-4). The attacker can now take advantage of the profile edit page in order to upload a malicious file by sending the SQLi payload sqli and the evil_file payload (5). The web app sends a query request to the database and the database answers (6-7). The web app now sends a writing request to the file-system in order to store the newly uploaded avatar evil_file (8), and finally the web app responds back to the attacker with the profileid page and the tuple(sqli) resulting from exploiting a SQLi in the editing request (9). The attacker exploits the evil_file created in (8), to read content from the file-system. The web app receives a request for the evil_file with payload fsi (10) and makes a request to the file-system for reading fsi (11-12). Finally, the web app sends the file back to the attacker (13).

It is worth remarking what happened in steps (6-7). Since we assumed that all requests made by the attacker are malicious actions, the only way the attacker has to proceed is performing a SQLi attack in the edit request. However, by reading the trace it can be easily seen that the SQLi is not used to bypass an authentication or extract information.

Listing 1.10: AAT #3 for accessing the file-system in Multi-Stage.

```
3  DB -> FS : writeFile(evil_file)
4  DB -> WebApp : tuple(new_file(evil_file))
5  WebApp -> i : dashboard.AuthCookie.tuple(new_file(evil_file))
6  i -> WebApp : file.fsi
7  WebApp -> FS : readFile(fsi)
8  FS -> WebApp : file(fsi)
9  WebApp -> i : file(fsi)
```
4.3 Concretization phase

We configured a safe environment where we ran DVWA and our Multi-Stage case study. We ran WAFEx and concretized the AATs it generated. The concretization was successful for all our case studies, actually showing how the attacker would perform the real attacks on both DVWA and Multi-Stage. The only example that WAFEx could not concretize is the AAT#2 in Multi-Stage. In that case, the attacker is supposed to exploit a SQLi for writing to the file-system. WAFEx was not able to concretize the trace since the user executing the database did not have the privileges to write to the file-system, which highlights, as we already stated, that the presence of a vulnerability does not imply its exploitability and that only a penetration testing phase can analyze such scenarios.

5 Related work

To the best of our knowledge, this paper is the first attempt to show how model-checking techniques and the standard DY attacker model can be used for the generation of attack traces where multiple vulnerabilities are used to violate a security property. There are, however, previous works that are closely related to what we presented in this paper and that are thus worth discussing.

Penetration testing remains the leading methodology for the security analysis of web applications. This is because the human component is crucial in evaluating the security of the web application. Tools like Wfuzz [36] or DotDotPwn [13] support the security analyst in finding the presence of vulnerabilities, but they do not give any clue on how a vulnerability can be used and they do not say if an attack that uses that vulnerability can actually be carried out.

In [1], Akhawe et al. presented a methodology for modeling web applications and considered five case studies modeled in the Alloy [18] language. The idea is similar to our approach, but they defined three different attacker models that should find web attacks, whereas we have shown how the standard DY attacker can be used. They also represent a number of HTTP details that we do not require that eases the modeling phase. Finally, and most importantly, they don’t take combination of attacks into consideration.

In [5], Büchler et al. presented SPaCiTE, a model-based security testing tool that starts from a secure (ASLan++) specification of a web application and, by mutating the specification, automatically introduces security flaws. SPaCiTE implements a mature concretization phase, but it mainly finds vulnerability entry points and tries to exploit them, whereas our main goal is to consider how the exploitation of one or more vulnerabilities can compromise the security of the web application.

The “Chained Attack” approach of [6] considered multiple attacks to compromise a web application. The idea is close to the one we present in this paper. However, the “Chained Attack” approach does not consider file-system vulnerabilities nor interactions between vulnerabilities, which means that with that formalization it would be impossible to represent a SQLi to access the file-system.
Finally, the “Chained Attack” approach requires an extra effort of the security analyst, who should provide an instantiation library for the concretization phase, while we use well-known external state-of-the-art tools.

The analysis in [10] was limited to SQLi for authentication bypass and data extraction attacks, which we used in this paper as the basis for considering SQLi for accessing the file-system and for modeling the Multi-Stage case study.

In [30], Rocchetto et al. model web applications to search for CSRF attacks. While they limit the analysis to CSRF, the idea and representation are close to ours and there could be useful interactions between the two approaches.

6 Conclusions and future work

We have proposed a formalization for the representation of web applications vulnerable to file-system attacks, and shown how the DY attacker model can be used in order to find and exploit attacks that violate security properties of web applications. Our approach is able to find multi-stage attacks to web applications that, to the best of our knowledge, no other tools can find, which involve the combined exploit of file-system and SQLi vulnerabilities. We have implemented a prototype tool called WAFEx that takes an ASLan++ specification of a web application and a concretization file, generates an AAT and automatically tests the resulting AAT against the real web application. WAFEx does not find payloads for exploiting vulnerabilities but rather makes use of state-of-the-art tool (Wfuzz [36] and sqlmap [32]) in order to find the proper payload. As a proof of concept, we have applied WAFEx to four real-life case studies.

As future work, we plan to extend our approach and WAFEx to cover other complex web application vulnerabilities such as Cross-Site Scripting as well as sophisticated multi-stage attacks involving the exploitation of multiple vulnerabilities. We also plan to extend WAFEx by introducing more functionalities for the automatic creation of the web application model and the concretization of multi-stage attacks.

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A Database

For the sake of completeness, we give here a quick description of the database formalization we first proposed in [10].

The database is defined by an if-elseif statement. In line (1), the database accepts messages for a sanitized query expressed by the uninterpreted function `sanitizedQuery()`. When the database receives a sanitized query, it is assumed that no SQLi is possible and thus the query can be performed only if executed with values that are stored in the database. The uninterpreted function `tuple()` is used to represent any information stored in the database and (2) enforces the constraint that a sanitized query can be performed only on a variable of the form `tuple(*)`, i.e., content stored in the database, where `*` acts as a wildcard that matches any possible parameter. The constant `no_tuple` is then returned as a response from the database to a sanitized query (2). `no_tuple` represents non-useful knowledge leaking from the database and, since a sanitized query is assumed safe against SQLi, it doesn’t increase the attacker’s knowledge.

Listing 1.11: Pseudo-code representing the basic behavior of the database (DB) as given in [10].

```java
if (WebApp -> DB: sanitizedQuery(SQLquery)){
    if (SQLquery == tuple(*)){ DB -> WebApp: no_tuple; }
}
elseif (WebApp -> DB: query(SQLquery)){
    if (inDB(SQLquery)){
        DB -> WebApp: tuple(SQLquery);
    }elseif (!inDB(SQLquery)){
        DB -> WebApp: no_tuple;
    }
}
```

The main elseif branch (3) defines how the database handles raw queries, which are expressed with the uninterpreted function `query()`. The validity of a query is expressed by the predicate `inDB()` and the corresponding Horn clause

\[
\text{db hc evil(M): inDB(sqli M)}
\]
where the SQLi payload is represented by the constant `sqli`. If the database receives a raw query that is valid, then `tuple(SQLquery)` is sent back (4), else the constant `no_tuple` is sent back (5).

**B The workflow of our approach (and tool)**

Fig. 2 shows the workflow of our approach, which comprises five main tasks. 

1. The security analyst uses the Burp proxy to record an HTTP trace of requests/responses of the web app.
2. The security analyst uses our model generator in order to translate the HTTP trace recorded by Burp into an ASLan++ model.
3. The security analyst completes the generated model in order to define the behavior and security goals he wants to test.
4. WAFEx takes in input the ASLan++ model that the security analyst has generated and invokes CL-AtSe \[34\], which model-checks the model and searches for an attack trace that violates the security goal defined by the security analyst. CL-AtSe generates an AAT as an MSC if an attack trace was found, which is then used by WAFEx, along with the concretization file, as input for the concretization engine that uses state-of-the-art-tools such as sqlmap and Wfuzz to concretize the AAT and apply it to test the real web app (5).
C Case studies

C.1 File Inclusion (DVWA)

Damn Vulnerable Web Application (DVWA) [15] is a vulnerable web app that provides an environment in which security analysts can test their skills and tools. DVWA is divided in examples implementing web pages vulnerable to the most common web app vulnerabilities. For the first case study, we consider the FI scenario, which is an example of a web app vulnerable to FI just like the running example we used in §3. The model is the one given in [Listing 1.6] and as goal we used the one in [Listing 1.7].

Abstract Attack Trace

We ran the model with WAFEx, which generated the AAT in [Listing 1.12] which shows an attack that exploits a FI vulnerability allowing the attacker \(i\) to get access to the file-system. The attacker \(i\) sends a request for the include page along with a file inclusion payload represented by the constant \(fsi\) (1). The web app performs a read request to the file-system (2), which responds to the web app with the requested file (3), and the web app sends back the file (4) to the attacker.

Listing 1.12: AAT that exploits a FI vulnerability.

```
1  i -> WebApp : include.fsi
2  WebApp -> FS: readFile(fsi)
3  FS -> WebApp : file(fsi)
4  WebApp -> i : include.file(fsi)
```

C.2 Unrestricted File Upload (DVWA)

In this case study, we used the UFU example from DVWA to show how simple it can be to represent an UFU vulnerability with our formalization. The example is indeed quite straightforward: a web app allows users to upload files. The model is shown in [Listing 1.13]. When it receives a request for file upload (1), the web app makes a request to the file-system entity for writing the file (2) and, since we assumed a writing operation always succeeds, the web app answers back to the client with the uploaded page (3). As goal, in [Listing 1.14] we check that a malicious file, represented by the constant \(evil_file\), is not part of the file-system.

Abstract Attack Trace

We ran the model with WAFEx, which generated the AAT in [Listing 1.15] which shows an attack that exploits an UFU vulnerability. The attacker \(i\) sends a request for uploading a file by sending the \(evil_file\) payload representing a malicious server side code (1). The web app

---

*In our case studies, we use the variable `Client` when the web app is expecting an interaction with a client. Since we assumed only malicious interactions with the web app [13], the variable `Client` will always be instantiated with the DY attacker \(i\) in concrete web app executions.*
sends a writing request to the file-system (2) and answers back to the client with the uploaded page. At the end of this execution, the file represented by the constant evil_file will be part of the file-system.

Listing 1.13: Pseudo-code representing an UFU vulnerability.

```plaintext
1 if( Client -> WebApp : uploaded.File ){
2    WebApp -> FS : writeFile(File);
3    WebApp -> Client : uploaded;}
```

Listing 1.14: Goal representing that a malicious file has been uploaded to the web application's file-system.

```
([](! inFS(evil_file)));
```

Listing 1.15: AAT that exploits an UFU vulnerability.

```
i -> WebApp : uploaded.evil_file
WebApp -> FS: writeFile(evil_file)
WebApp -> i : uploaded
```

### C.3 SQLi read (DVWA)

In this case study, we used the SQLi example from DVWA to show how it is possible to exploit a SQLi for reading content from the file-system. This example from DVWA was meant to show how a SQLi vulnerability can be exploited for extracting data from the database. However, WAFEx was able to generate a wider set of attack traces showing that the SQLi in DVWA could also be used for reading files from the file-system. Consider a web app that accepts a value representing a user id that is used in a `SELECT` query for retrieving and showing details about that user. The model is given in Listing 1.16. The web app accepts a request for the `userid` page along with the `IDvalue` value (1). The web app then performs a query to the database by sending a query request (2). The web app waits to receive back the result of the query from the database (3) and, upon receiving `tuple(Response)`, it sends to the user the page `userid` and the result of the query `tuple(Response)` [Listing 1.17] shows the file-system access goal that we defined in which the attacker should not be able to know `file()`.

Listing 1.16: Pseudo-code representing a SQLi for file reading vulnerability.

```
1 if(Client -> WebApp : userid.IDvalue){
2    WebApp -> DB : query(IDvalue);
3    if(DB -> WebApp : tuple(Response)){
4        WebApp -> Client: userid.tuple(Response);}}
```

Listing 1.17: Goal representing that the attacker knows the content of the file-system.

```
([](!iknowledge(file(*)));)
```
**Abstract Attack Trace** We ran the model with WAFEx, which generated the AAT in Listing 1.18, which shows an attack in which the attacker $i$ is able to exploit a SQLi vulnerability in order to read from the file-system. The attacker $i$ sends the concatenation of `userid` with the SQLi payload `sqli` and the `fsi` payload (1). The web app sends a query to the database (2), which, thanks to our formalization, can be forced into performing a reading operation to the file-system (3). The file-system checks that the file is a valid file and answers back to the database wrapping the `fsi` payload with the `file()` function (4). The database wraps the answer from the file-system with `tuple()` and sends it back to the web app (5). Finally, the web app forwards back to the attacker the result of the query along with the `userid` page (6).

Listing 1.18: AAT that exploits a SQLi for reading files from the file-system.

```plaintext
1  i -> WebApp : userid . sqli . fsi
2  WebApp -> DB : query (sqli . fsi)
3  DB -> FS : readFile (fsi)
4  FS -> DB : file (fsi)
5  DB -> WebApp : tuple (file(fsi))
6  WebApp -> i : userid . tuple (file(fsi))
```

C.4 Multi-Stage

Multi-Stage implements a typical HTTP login phase in which users can log into the system by providing username and password credentials. The web app performs a query to the database in order to verify the credentials and grant access to a restricted area. The restricted area allows users to view other users’ profiles and modify their own personal information, which are Name, Surname, Phone number, and it allows for the upload of a personal image to use as avatar.

We check the web app for file reading attacks i.e., we want to generate multi-stage attack traces showing how an attacker can exploit file-system and SQLi vulnerabilities web app’s file-system. Listing 1.19 shows a model for such a web app, which has three branches of an if-else statement, each one responding to a different request.

Listing 1.19: Pseudo-code representing the Multi-Stage web app.

```plaintext
1  if(Client -> WebApp : login. Username . Password){
2      WebApp -> DB : query (Username . Password);
3      if(DB -> WebApp : tuple (SQLresponse)){
4          AuthCookie := fresh ();
5          sessionValue (AuthCookie);
6          WebApp -> Client : dashboard . tuple (SQLresponse).
7                  AuthCookie , ;
8      }elseif (Client -> WebApp : profileid . Id. AuthCookie){
9          if (sessionValue (AuthCookie)){
10             WebApp -> DB : query (Id);
11             if (DB -> WebApp : tuple (SQLresponse)){
```
The first branch (1) represents how the web app responds to a login request in which the client sends credentials (Username and Password). When the web app receives the login request, it performs a query to the database in order to verify the received credentials (2). If the credentials are correct, then the database responds back with SQLresponse wrapped with the function tuple() (3), and then the web app creates a variable AuthCookie (4), marks it as a session value by using the sessionValue predicate (5), and finally responds to the client by sending the dashboard page, the result of the query tuple(SQLresponse) and the cookie AuthCookie (6).

The second branch (7) responds to the request to view a user’s profile. The client sends a request to the web app for the profileid page with the Id value for the user’s profile to view and a AuthCookie value that is used to verify that the request comes from an authenticated user. The web app first checks if the cookie provided in the request is a valid session value (8) and, if it is, then the web app performs a query to the database by sending the Id of the profile that has been requested (9). If the database sends the result of the executed query tuple(SQLresponse) (10), then the web app responds to the client by sending the profileid page and tuple(SQLresponse) (11).

The third branch handles the edit profile request. The client sends a request to the web app for the editing page edit along with values for Name, Surname, Phone, Avatar and an AuthCookie value (12). The web app checks if the cookie provided in the request is a valid session value (13), and if it is, then the web app performs a request to the database to edit the values for Name, Surname, Phone and Avatar (14). Since editing profile values is performed with an UPDATE query, the web app checks that the answer from the database is tuple(SQLresponse) (15), and then performs a writing operation to the file-system to save the Avatar value (16). Since we assumed the writing operation to always succeed, the web app sends, without further checks, the page profileid and the result of the query tuple(SQLresponse) to the client (17).

The last part of the model shows how to deal with remote code execution §3.4. We include in the specification of the web app a typical server-side code that would allow an attacker to have reading access over the web app’s file-system. The web app can receive a request for evil_file (18) only if evil_
file is part of the file-system (19). If that is the case, then evil_file allows an attacker to perform a reading request to the file-system (20), where the FilePath variable is used to specify the file that has to be retrieved. If the file-system responds back to the web app with file(FilePath) (21), then the web app will forward file(FilePath) back to the client (22).

We check the web app for file reading attacks (Listing 1.20).

Listing 1.20: Goal representing that the attacker knows the content of the file-system.

\[ \neg (\text{iknowledge}(\text{file}(*)) ) \]

Abstract Attack Trace See §4.2

D Implementation in ASLan++

We now present the details of how we implemented our formalization using the formal language ASLan++. It is worth remembering that our approach is not strictly related to ASLan++, in fact our approach is general enough that it could be quite straightforwardly used with other specification languages and/or other reasoners implementing the Dolev-Yao attacker model.

D.1 Skeleton model

We now present the ASLan++ code of a skeleton model that implements all the aspects described in §3. This skeleton is intended to be a base ASLan++ model from which a security analyst can start the creation of a web app model. We first describe agents, variables, constants, facts and uninterpreted functions (Listing 1.21), and then describe the clauses that define the behavior of SQLi and file-system attacks (Listing 1.22), the file-system entity (Listing 1.24), the database entity (Listing 1.23) and the web app entity (Listing 1.25).

We assume that the reader is familiar with the syntax of ASLan++; details can be found, for instance, in [3,35] and in the documents referenced there.

Listing 1.21: ASLan++ code of the symbols used in the skeleton of a web app.

1 specification Skeleton
2 channel_model CCM
3 entity Environment{
4 symbols
5 webapplication, database, filesystem:agent;
6
7 % Malicious payload
8 sqli,fsi,evil_file:text;
9
10 % Database
11 nonpublic inDB(message):fact;
12 nonpublic query(message):message;
nonpublic sanitized(message):message;
nonpublic tuple(message):message;
nonpublic no_tuple:text;

% Filesystem
nonpublic readFile(message):message;
nonpublic file(message):message;
nonpublic inFS(message):fact;
nonpublic isInFS(message):fact;
nonpublic writeFile(message):message;
nonpublic no_file:text;

% Sessions
nonpublic sessionValue(message):fact;

% request
http_request(message,message,message):message;

% response
http_response(message,message):message;

% separator
s, none : text;

Lines 1–3 begin the skeleton specification by stating a name for the specification (Skeleton), the channel model used (CCM) and by introducing the outermost entity (Environment). The symbols section of the environment entity begins in line 4. We define the constants representing the agents involved in the communication (5): the web app (webapplication), the database (database) and the file-system (filesystem). In line 8, we define the abstract payload that the DY attacker will use for attacking the web app: sqli for SQLi attacks, fsi for file-system attacks and evil_file for executing arbitrary server-side code. In lines 11–15, we define predicates and uninterpreted functions used for implementing the database behavior as described in §3.3. In lines 18–23, we define predicates and uninterpreted functions used for implementing the file-system behavior as described in §3.2. In line 26, we define the predicate that is used to describe when a constant is a session value. In lines 29 and 31, we define two uninterpreted functions (http_request and http_response) that are used to define an HTTP request and an HTTP response, respectively. In line 32, we define the constant s, which is used as separator in the list of parameters of an HTTP request, and the constant none, which is used for optional parameters.

The uninterpreted function http_request has three parameters: (1) the web page being requested, (2) the list of parameters and (3) a cookie value. The web page is defined with a constant, while the list of parameters as a concatenation of text of the form const.s.Val, where const is a constant representing a key and Val is a variable representing the value for the const key (and s is used as separator). The cookie value is optional and is represented with a constant.

The uninterpreted function http_reponse has two parameters: (1) the web page sent back to the client and (2) the content of the response, which is a concatenation of constants, variables and uninterpreted functions that represent
Our skeleton defines the behavior of SQLi and file-system attacks, as described in §3.3 and §3.2 with a series of Horn clauses, shown in Listing 1.22.

Listing 1.22: ASLan++ code of the Horn clauses used in the skeleton.

```
1 % DATABASE (behavior)
2 db_hc_ev(M) : inDB((sqli .?) .M);
3 db_hc_ev_2(M) : inDB(sqli .M);

4 % FILESYSTEM (behavior)
5 fs_hc_ev(M) : inFS(fsi .M);
6 fs_hc_ev_2(M) : inFS((fsi .?) .M);
7 fs_hc(M) : inFS(M) :- isInFS(M);
```

Lines 2–3 define clauses for SQLi attacks, 6–8 define the behavior of a file-system attack. It is worth noticing two things. First, in ASLan++, if we write `sqli .M` we mean a message that is a composition of exactly 2 texts. Lines 3 and 7 are used to define an arbitrary arity for a message payload. Second, in order to have the Horn clause to evaluate to true whenever a new file is added to the file-system, in line 8, we define that `inFS()` is true for a message `M` whenever the predicate `IsInFS()` for the message `M` is true. We use the `IsInFS()` predicate in the writing branch of the file-system entity in order to state that a new file is now part of the file-system (Listing 1.23).

Our skeleton defines three entities: the file-system entity (Listing 1.23), the database entity (Listing 1.24) and the web app entity (Listing 1.25). These three entities are subentities of the session entity that in ASLan++ is generally used for instantiating the model.

The Filesystem entity in (Listing 1.23) follows the pseudo-code that we presented in §3.2. The while loop in line 8 wraps the entity body content and defines that the file-system entity is actively listening for incoming communications. Upon receiving a reading operation (10), if the predicate `inFS()` holds for the variable `Path` (11), the file-system answers back with `file(Path)` (12). If the predicate `inFS()` doesn’t hold (14), the constant `no_file` is sent back instead (15). Two things are worth noticing: the use of `select-on` and the introduction of nonces. We implemented the two main branches as `select-on` since in ASLan++ the semantics of `select-on` saves one or more transitions with respect to `if` when the ASLan++ specification is translated into a transition system. The introduction of nonces in any on-going message is used to avoid spurious man-in-the-middle attacks between the entities.

Listing 1.23: ASLan++ code of the file-system entity.

```
1 entity Session(Webapplication, Database, Filesystem: agent) {
2 entity Filesystem(Webapplication, Actor: agent){
3     symbols
4     Nonce: text;
```
The Database entity in Listing 1.24 implements the behavior described in §3.3. We introduce two more branches that define the communication between the database and the file-system entity. Lines 20–26 define that the database can communicate with the file-system entity to perform a reading operation. Upon receiving a SQL query, in case the Horn clause `inDB()` holds (20), the database can perform a reading operation on the file-system (22-23) and, if the file-system answers back with a file (24), the database entity will wrap the answer with the uninterpreted function `tuple()` and forward it back to the web app (25). Lines 27–32 define that the database can communicate with the file-system entity to perform a writing operation. Upon receiving a SQL query, in case the Horn clause `inDB()` holds (27), the database can perform a writing operation on the file-system (28-31). It is worth noticing the introduction of the uninterpreted function `newFile()`. When the database is performing a writing operation, it will send back to the web app the uninterpreted function `tuple()` wrapping the uninterpreted function `newFile()`, which notifies the web app the creation of a new file.

Listing 1.24: ASLan++ code of the database entity.
The Webapplication entity in Listing 1.25 is written as a series of select-on branches, where the guard of each select-on defines an HTTP request the web app can handle and the body for that branch defines the behavior of the web app upon receiving that HTTP request. This is the only part of our skeleton that changes accordingly to the web app being analyzed.

Listing 1.25: ASLan++ code of the web application entity.

```plaintext
entity Webapplication(Actor, Database, Filesystem: agent) {
symbols
% all the symbols used in the body of this
% entity in the body below
body { % write the behavior of the web app.
  %select{
    % on( ? -> Actor) : { % do something here;
    % }...
  }
}
}
```

The final part of the skeleton (Listing 1.26) implements the instantiation of the web app, file-system and database entities carried out by the session entity (1-5), the definition of the goals (6-8) and the instantiation of the session entity carried out by the environment entity (9-11).

Listing 1.26: ASLan++ code of the session body.

```plaintext
body{
```
new Webapplication(webapplication, database, filesystem);
new Database(webapplication, database, filesystem);
new Filesystem(webapplication, filesystem);
}
goals %of session
goal_label: % put your security goal here
}
body{ %of Environment
new Session(webapplication, database, filesystem);
}}

D.2 ASLan++ specifications of our case studies

In this section, we give the ASLan++ codes that implement the DVWA case studies and the Multi-Stage case study we presented in §4. The ASlan++ codes of this section are meant to fill the empty spaces of the ASLan++ skeleton for the web app entity in §D.1.

File inclusion (DVWA) We used the lesson named “File Inclusion” from Damn Vulnerable Web Application (DVWA) [15]. The web app entity (Listing 1.27) has one branch that defines the behavior of the web app upon receiving a request for including a file. Lines 1–3 define symbols used by the web app. Lines 6–8 define that the web app can handle a request for page include with parameters page.s.?Path and without cookie (none). In line 9, a nonce is generated to ensure a fresh communication, in lines 10–11, the web app performs a reading action on the file-system and in line 12, the web app sends an HTTP response back to the client with the include page and file(Path).

Listing 1.27: ASLan++ code for the “File Inclusion” lesson of DVWA.

symbols
IP: agent;
NonceWA, NonceDB: text;
body{
while(true){
select{
% implementing include functionality
on( *->* Actor : IP. http_request(include, page.s.?Path, none). tag1):{
NonceWA := fresh();
Actor *->* Filesystem : readFile(Path). NonceWA;
Filesystem *->* Actor : file(Path). NonceWA;
Actor *->* IP : http_response(include, file(Path));
}}
}

As goal (Listing 1.28), we define that the attacker should not be able to access something that is function of file().

The constant tag1 is used for concretization purposes, see §E for further details.
Upload (DVWA) We used the lesson named “Upload” from DVWA. The web app entity [Listing 1.29] has one branch that defines the behavior of the web app upon receiving a request for uploading a file. Lines 1–3 define symbols used by the web app. Lines 6–10 define that the web app can handle a request for page upload with parameters file.s.?Path and without cookie (none). In line 8, a nonce is created to ensure a fresh communication and in line 9, the web app communicates with the file-system for writing the file Path to the file-system. Finally, the web app sends back to the client an HTTP response with the page upload and the uploaded file file(Path). It is worth noticing that the web app does not have to wait for an answer from the file-system for the writing operation since we assumed that no access policies are in place and thus any writing operation will always succeed (see §3.2).

Listing 1.29: ASLan++ code for the “Upload” lesson of DVWA.

As goal [Listing 1.30] we check that a malicious file, represented by the constant evil_file is not part of the file-system.

SQLi read (DVWA) We used the lesson named “SQL Injection” from DVWA. The web app entity [Listing 1.31] has one branch that defines the behavior of the web app upon receiving a request for querying the database. Lines 1–4 define symbols used by the web app. Lines 7–9 define that the web app can handle a request for page viewUser with parameters userId.s.?IDvalue and without a cookie (none). In Line 9, a nonce is generated for ensuring a fresh communication, in lines 10–11, the web app performs a SQL query communicating with the
database entity and in lines 12–13, the web app verifies that \texttt{tuple()} is sent back from the database and sends an HTTP response back to the client.

Listing 1.31: ASLan++ code for the file-system access of the “File Inclusion” lesson of DVWA.

```plaintext
1 symbols
2 IDvalue, SQLquery, SQLresponse: message;
3 IP: agent;
4 NonceWA: text;
5 body{
6 while (true){
7     select{
8         on(? *->* Actor: ?IP.http_request(viewUser, userId.s.?IDvalue, none).tag1):{
9             NonceWA := fresh();
10             SQLquery := IDvalue;
11             actor *->* Database: query(SQLquery).NonceWA;
12             select(on(Database *->* Actor: tuple(?SQLresponse).NonceWA):{
13                 Actor *->* IP: http_response(viewUser, tuple(SQLresponse));
14             });
15         }
16     }
17 }
18 }
```

As goal we use the same goal that we defined in Listing 1.28 that states the attacker should not be able to access something that is function of file().

Multi-Stage The ASLan++ model for the web app described in §4.2 is given in Listing 1.32 Lines 1-6, define symbols used by the web app. The body of the web app entity (lines 7–47) describes how the web app can handle four different HTTP requests.

The first branch (10–19) handles a login process, where the web app receives a request for page \texttt{index} with parameters \texttt{usr.s.?Username.s.pwd.s.?Password} and without cookie (\texttt{none}). The web app then creates a nonce to ensure a fresh communication (11) and queries the database with the provided username and password (12–13). If the web app receives \texttt{tuple(?SQLresponse)} as a response for the query (15), it instantiates a variable \texttt{AuthCookie} to a fresh value, marks it as a session value and sends it back to the client in an HTTP response (16–18).

The second branch (20–27) handles the possibility for a logged-in user to view another user’s profile, where the web app receives a request for page \texttt{profileId} with parameters \texttt{id.s.?Id} and cookie value \texttt{?AuthCookie}. The web app checks if the value of \texttt{AuthCookie} is actually a valid session value (21) and, if that is the case, performs a query to the database (22–24). The web app verifies to receive \texttt{tuple(SQLresponse)} as answer from the query (25) and, if that is the case, sends an HTTP response back to the client with the \texttt{profileId} page, the result of the executed query (\texttt{tuple(SQLresponse)}) and the session cookie value \texttt{AuthCookie} (26).

The third branch (28–37) handles the possibility for a logged-in user to edit a profile where the web app receives a request for page \texttt{edit} with parameters
name.s.?Name.s.surname.s.?Surname.s.phone.s.?Phone.s.avatar.s.?Avatar and cookie value ?AuthCookie. The web app checks if the value of AuthCookie is actually a valid session value (29) and, if that is the case, performs a query to the database for editing the user’s details (30–32). If the database answers with tuple(?SQLresponse) (33), the web app communicates with the file-system in order to save the avatar file just uploaded (34–35), and finally answers to the client with an HTTP response redirecting the user to the page profileId and providing the result of the executed query and the session cookie value (36).

The fourth branch (40–47) simulates the presence of a malicious server side script. Line 40 defines that the web app can answer to a request for page evil_file with parameters file.s.?Path and no cookie (none) and line 41 specifies that the page evil_file should be part of the file-system and the variable ?Path is different from evil_file (this aims to avoid spurious traces, where the DY attacker sends requests of the form http_request(evil_file,file.s.evil_file,none), where he exploits evil_file for reading evil_file).

If the conditions on line 41 are satisfied, it means that evil_file has been uploaded on the remote file-system and that the attacker is trying to use it for accessing a file different from evil_file. The web app creates a nonce to ensure a fresh communication (42), performs a reading operation on the file-system (43–45), and sends an HTTP response to the client with the page evil_page and the content of the file just read (file(Path)) (46).

Listing 1.32: ASLan++ code for the Multi-Stage case study.

```plaintext
1 symbols
2   Id: text;
3   Username , Password , AuthCookie , Path , Name , Surname ,
   Phone , Avatar: message;
4   IP: agent;
5   SQLquery , SQLresponse , Search: message;
6   NonceWA: text;
7 body{
  8 while (true) {
  9     select{
 10        on( ? *->* Actor: ?IP.http_request(index,usr.s.?Username.s.pwd.s.?Password, none).tag1):{
 11           NonceWA := fresh();
 12           SQLquery := Username.Password;
 13           Actor *->* Database : query(SQLquery).NonceWA;
 14        select{
 15           on(Database *->* Actor : tuple(?SQLresponse).NonceWA)
 16           :{
 17              AuthCookie := fresh();
 18              sessionValue(AuthCookie);
 19              Actor *->* IP: http_response(dashboard, tuple(
 20                 SQLresponse).AuthCookie);
 21          }}}}}
 22        on( ? *->* Actor: ?IP.http_request(profileId, id.s.?Id,  
 23            ?AuthCookie).tag3 ) : {
```
select { on(sessionValue(AuthCookie)):
    SQLquery := Id;
    NonceWA := fresh();
    Actor *->* Database : query(SQLquery).NonceWA;
    select { on(Database *->* Actor : tuple(SQLresponse)):
        Actor *->* IP : http_response(profileId, tuple(
            SQLresponse).AuthCookie);
    }}

on( ? *->* Actor : ?IP.http_request(edit, name.s.?Name.s.
surname.s.?Surname.s.phone.s.?Phone.s.avatar.s.?Avatar, ?AuthCookie).tag2):
select { on(sessionValue(AuthCookie)):
    SQLquery := Name.Surname.Phone.Avatar;
    NonceWA := fresh();
    Actor *->* Database : query(SQLquery).NonceWA;
    select { on(Database *->* Actor : tuple(?SQLresponse).
        NonceWA):
        NonceWA := fresh();
        Actor *->* Filesystem : writeFile(Avatar).NonceWA;
        Actor *->* IP : http_response(profileId, tuple(
            SQLresponse).AuthCookie);
    }}

% this branch represents an uploaded server-side code
on( ? *->* Actor : ?IP.http_request(evil_file, file.s.?Path, none).tag4):
select { on(inFS(evil_file) & evil_file != Path):
    NonceWA := fresh();
    Actor *->* Filesystem : readFile(Path).NonceWA;
    %assert b: false;
    Filesystem *->* Actor : file(Path).NonceWA;
    Actor *->* IP : http_response(evil_file, file(Path));
}}

As goal, once again, we use the same goal we defined in [Listing 1.28] that states the attacker should not be able to access something which is function of file().

E Concretization file

Along with the ASLan++ model, the security analyst has to define a concretization file that is used by WAFEx to carry out an automatic analysis. The concretization file is written in the JSON format and consists of the information:
- **domain**: the IP address of the server hosting the web app.
- **tag#**: The ASLan++ model will have a tag value tag# associated to each HTTP request, where # is an integer number. This tag value is used to map an abstract request in the ASLan++ file to the concretization details in the concretization file. Each tag# defines a JSON object with the following information:
- **url**: the URL of the page.
- **method**: whether the request to be performed is GET, POST, PUT or CREATE.
- **mapping**: a JSON dictionary that maps abstract parameters keys in the ASLan++ model to the real parameters keys.
- **params**: a JSON dictionary that defines the parameters required for performing the request. We use the placeholder ? to define that a value of a parameter has to be decided at runtime, and _ to define that the value for that parameter is a file.
- **cookies**: a JSON dictionary that defines the cookies required for performing the request. We use ? to define that a value of a cookie has to be decided at runtime.
- **tables**: a JSON dictionary that maps real parameters keys to the corresponding columns in the database in the form **table.column**.
  - **abstract_page**: for each abstract page represented in the ASLan++ model, we define the pair abstract_page:content_to_check, where content_to_check is a string that WAFEx will verify to be part of abstract_page in order to ensure the page has been correctly retrieved.
  - **evil_file**: defines the local location of the malicious server side script that needs to be used.

The concretization file for the Multi-Stage case study is reported in Listing 1.33.

```
Listing 1.33: Concretization file for the Multi-Stage case study.

1 {"domain": "127.0.0.1",
 2 "tag1": {
 3 "url": "https://127.0.0.1/index.php",
 4 "method": "POST",
 5 "mapping": { "usr": "username", "pwd": "password" },
 6 "params": { "username": "?", "password": "?" },
 7 "tables": {"username":"users.username", "password":"users.password"},
 8 "tag2": {
 9 "url": "https://127.0.0.1/profile.php",
10 "method": "POST",
11 "params": { "avatar": "_", "phone": "?", "surname": "?", "name": "?" },
12 "mapping": { "avatar": "avatar" },
13 "tables": {"name":"users.name","surname":"users.surname","phone":"users.phone","avatar":"users.avatar"},
14 "tag3": {
15 "url": "https://127.0.0.1/profile.php",
16 "method": "POST",
17 "params": { "id": "?" },
18 "mapping": { "id": "id" },
19 "tables": {"id":"users.id"},
20 "tag4": {
21 "url": "https://127.0.0.1/index.php",
22 "method": "GET",
```

"params" : { "file" : "_" },
"mapping" : { "file" : "file" }},
"dashboard" : "Welcome",
"profileId" : "Welcome",
"files" :{
"evil_file" : "/home/evil_file.txt"}