Easy to Fool? Testing the Anti-evasion Capabilities of PDF Malware Scanners

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Abstract

Malware scanners try to protect users from opening malicious documents by statically or dynamically analyzing documents. However, malware developers may apply evasions that conceal the maliciousness of a document. Given the variety of existing evasions, systematically assessing the impact of evasions on malware scanners remains an open challenge. This paper presents a novel methodology for testing the capability of malware scanners to cope with evasions. We apply the methodology to malicious Portable Document Format (PDF) documents and present an in-depth study of how current PDF evasions affect 41 state-of-the-art malware scanners. The study is based on a framework for creating malicious PDF documents that use one or more evasions. Based on such documents, we measure how effective different evasions are at concealing the maliciousness of a document. We find that many static and dynamic scanners can be easily fooled by relatively simple evasions and that the effectiveness of different evasions varies drastically. Our work not only is a call to arms for improving current malware scanners, but by providing a large-scale corpus of malicious PDF documents with evasions, we directly support the development of improved tools to detect document-based malware. Moreover, our methodology paves the way for a quantitative evaluation of evasions in other kinds of malware.

1 INTRODUCTION

Malware scanners, or shortly scanners, are software tools that detect malicious files, or in brief, malware. Two common types of scanners are static and dynamic scanners. *Static scanners* reason about a file by examining its content without actually running it. In contrast, *dynamic scanners* examine the behavior of a file at run-time, either by executing it (e.g. Windows executable), or by opening it in the appropriate application (e.g. Adobe Reader for PDF files) or an emulator of such an application.

Perhaps as old as the emergence of scanners [60] are *evasions*, which are used by attackers to circumvent scanners. Also known as "logic bombs" in earlier work [28], evasions try to fool scanners through a variety of static techniques, such as code obfuscation, and dynamic techniques, such as checking the run-time environment to behave benignly when the environment appears to be a scanner. The ultimate goal is the same across all evasions: bypass the scanner, while preserving the infection capabilities of the file to compromise the victim's security.

As scanners are constantly improving their abilities to detect malware, evasion techniques are evolving as well. To bypass modern defenses that deploy both static and dynamic analysis, attackers may combine evasions, which can lead to side-effects that have to be assessed. Vendors of malware scanners must keep fighting new evasion techniques and their combinations, just like new attacks. It is therefore crucial for vendors to understand which evasions to address first and how evasions and their combinations impact their scanners.

In this work we present a systematic methodology to quantitatively study and compare evasions. The methodology is applicable to any type of malware and their corresponding scanners. The main goal of the methodology is to determine how effective evasions are, or to put inversely, how effective scanners are despite the presence of evasions. In addition, the methodology allows for measuring unintended side-effects of an evasion, e.g., turning an undetected file into a detected one, and for measuring the effect of combining multiple evasions.

We use our methodology to study evasions for PDF files. Document-based malware attacks are a prevailing problem [3, 29, 52]. These attacks use email or web traffic to deliver malicious documents to victim systems. Then they compromise the system's security by exploiting a vulnerability in the document processing application (e.g., a PDF exploit) or by using legitimate features of the document processing application itself (e.g., embedding an executable file). The attacker's goal is to execute arbitrary machine code or code in a powerful language supported by the client applications (e.g., Visual Basic scripts for Office files). As most organizations need to be able to receive or download files in different document formats, these attacks are particularly difficult to prevent compared to attacks that use executable file formats only. Yet, malicious documents are as powerful as malicious executables because they can lead to arbitrary code execution.

Unfortunately, despite the widespread use of document files and works that study their evasions [8, 12, 20, 46, 66, 75, 78], little is currently known about the effectiveness of document evasion techniques, their combinations, and the dependence of evasion effectiveness on other malware components, such as the exploit used by a malicious document. Using our methodology, we study evasion techniques for PDFs and evaluate their effectiveness in bypassing state-of-the-art PDF scanners. To this end, we develop a novel framework, called Chameleon, that enriches existing malicious PDF documents with one or more evasions. Chameleon automatically creates PDF exploits with evasions and validates whether the generated exploits work successfully despite the evasion. Based on 1,395 documents generated by Chameleon, we study 41 widely used PDF scanners (34 of which are available via VirusTotal) and report a detailed analysis of the results.

The findings of our study include the following:

- Except for one studied scanner [36], none of the 41 scanners is immune to evasions. Each of them can be fooled by some evasions into misclassifying a malicious document as benign. This result is particularly surprising because the vulnerabilities exploited in our malicious documents have been known for several years.
- There are huge variations across different scanners. While some scanners identify most malicious documents despite evasions, other scanners are fooled by more than 80% of all evasions.
- We identify three combinations of evasions that are particularly dangerous as they can mislead all but two scanners.
- The attack mechanism used in a document influences the effectiveness of evasions. For example, an exploit that relies only on JavaScript can often be effectively concealed by obfuscating the JavaScript code.
- Evasions can be easily combined in an automated way to bypass both static and dynamic scanners.
- Evasions may have side effects and can become counterproductive by making scanners suddenly detect an otherwise undetected malicious document.

The results of this study are relevant for several groups of people. First, our methodology will help researchers to study and rank evasions by their effectiveness in a consistent manner. Moreover, our study sheds light on the anti-evasion problems that state-of-the-art document scanners suffer from. Second, vendors of security scanners, e.g., anti-virus or sandbox solution vendors, can learn and use our findings to further harden their solutions against evasion techniques. Third, users and organizations that need to defend themselves against malware attacks obtain a better understanding of how effective their deployed security solutions are, particularly for PDF-based attacks. We believe that publicly sharing the knowledge about evasions and their effectiveness is the best step toward effectively mitigating potential attacks. In addition, we are closely collaborating with vendors of scanners to make them aware of their current weaknesses.

In summary, we make the following contributions:

- **Evasion assessment methodology:** We propose a methodology to quantitatively study the effectiveness of evasions on a large scale. This methodology can be used for all types of malware and their corresponding scanners.
- **Chameleon framework:** We implement our methodology for PDF exploits in Chameleon, a novel framework that automatically transforms malicious PDF documents into evasive documents.
- **A benchmark test suite:** We make a corpus of 1,395 evasive PDF files generated by Chameleon publicly available, to foster future work on evaluating and improving PDF security scanners.
- **An in-depth study of evasions for document-based malware:** We conduct a large-scale study of the effectiveness of 19 PDF evasions on a set of 41 scanners. Our findings show widely used scanners to be easily fooled by evasions, motivating work on better-coping with evasions.

2 A METHODOLOGY FOR ASSESSING EVASIONS

To study the anti-evasion capabilities of malware scanners, we present a generic methodology to study evasions and their effect on scanners. The methodology is designed to address a set of research questions presented in Section 2.1. To address these questions, we define several metrics that measure how evasions influence the outcome of malware scanners (Section 2.2). Our methodology assumes that possibly malicious files are analyzed by scanners, and that these files may contain evasions. *File* here means any type of file ranging from executables (e.g., Android apps) to document files (e.g., Office documents). *Scanner* here means a software tool that classifies a file either as malicious or as benign. Finally, *evasion* refers to a technique aimed at concealing the fact that a file is malicious.

2.1 Research Questions

We focus on the following research questions (RQs):

- **RQ1:** How accurately do the scanners classify malicious and benign files in the presence of evasions?
- **RQ2:** How effective are the evasions at fooling specific scanners?
- **RQ3:** Which evasions are most effective?
- **RQ4:** Do some evasions have the opposite of the expected effect, i.e., do they cause scanners to detect malicious files that are missed otherwise?
- **RQ5:** Are there combinations of evasions that are harder to detect than the individual evasions?
- **RQ6:** Does the effectiveness of an evasion depend on the exploit or the payload used in a malicious file?

2.2 Metrics for Assessing Evasions

To address the above questions, we define several metrics. For illustration, consider the set of example files in Table 1. There are two single evasions, called e_1 and e_2, and one evasion that is a combination of the two, called $e_{1,2}$. Lines 1–16 in the table represent malicious files. Each malicious file is based on an exploit, a payload, and optionally, also an evasion. The last two lines of the table represent two benign files without any payload, exploit, or evasion. For each file, the table shows if two (hypothetical) scanners classify the file as malicious or benign.

For a set E of evasions, a set S of scanners, and a set F of malicious files, we use the notation f^e for a file $f \in F$ that uses an evasion $e \in E$. The function $mal : S \times F \rightarrow Boolean$ indicates whether a scanner classifies a given file as malicious. Inversely, the notation $\neg mal(s, f)$ means that a scanner s classifies a file f as benign. For a set F_{ben} of benign files that do not contain any payload, exploit, or evasion, and a set F of malicious files from a set of payloads, optionally a set of exploits, and a set E of evasions, we define the following formulas to measure scanners' performance in dealing with evasions.

Recall and false positive ratio. We evaluate a scanner's accuracy in distinguishing malicious from benign files by measuring recall and false positive (FP) ratio.

Table 1: Example files to illustrate the metrics.

#	Evasion	Exploit	Payload	Scanner outcome	
				s_1	s_2
1	–	x_1	p_1	malicious	benign
2	–	x_1	p_2	malicious	benign
3	–	x_2	p_1	malicious	malicious
4	–	x_2	p_2	malicious	malicious
5	e_1	x_1	p_1	malicious	malicious
6	e_1	x_1	p_2	malicious	malicious
7	e_1	x_2	p_1	malicious	benign
8	e_1	x_2	p_2	malicious	benign
9	e_2	x_1	p_1	benign	benign
10	e_2	x_1	p_2	benign	benign
11	e_2	x_2	p_1	malicious	benign
12	e_2	x_2	p_2	malicious	benign
13	$e_{1,2}$	x_1	p_1	benign	malicious
14	$e_{1,2}$	x_1	p_2	benign	malicious
15	$e_{1,2}$	x_2	p_1	benign	malicious
16	$e_{1,2}$	x_2	p_2	benign	malicious
17	–	–	–	benign	benign
18	–	–	–	malicious	benign

DEFINITION 1 (RECALL). *Given a scanner s and a set F of malicious files, the recall of s is:*

$$recall(s, F) = \frac{|\{f \in F \mid mal(s, f)\}|}{|F|}$$

The FP ratio is computed for each scanner s on a set F_{ben} of benign files. Here we use benign files only, because these are the files where a scanner might mislead users by erroneously classifying a file as malicious.

DEFINITION 2 (FP RATIO). *Given a scanner s and a set F_{ben} of benign files, the FP ratio of s is:*

$$FP\ ratio(s, F_{ben}) = \frac{|\{f \in F_{ben} \mid mal(s, f)\}|}{|F_{ben}|}$$

For the example files in Table 1, recall and FP ratio are as follows.

$$recall(s_1) = \frac{10}{16} = 0.625 \qquad recall(s_2) = \frac{8}{16} = 0.5$$

$$FP\ ratio(s_1) = \frac{1}{2} = 0.5 \qquad FP\ ratio(s_2) = \frac{0}{2} = 0.0$$

Effectiveness of evasions. We measure the success of an evasion in bypassing a scanner for a set of malicious files. Intuitively, we compare the outcome of a scanner for each file with an evasion to the outcome of the scanner for the exact same file without the evasion.

DEFINITION 3 (EVASION EFFECTIVENESS). *Given a scanner s and a set F of malicious files, the effectiveness of an evasion e is:*

$$eff(e, s, F) = \frac{|\{f \in F \mid mal(s, f) \wedge \neg mal(s, f^e)\}|}{|\{f \in F \mid mal(s, f)\}|}$$

If the scanner does not classify any file as malicious, which would lead to a division by zero, the effectiveness is defined to be zero.

For example, to compute the effectiveness of e_1 in Table 1, we compare row 5 with row 1, row 6 with row 2, row 7 with row 3, and row 8 with row 4. As a result, the effectiveness for the two scanners s_1 and s_2 is:

$$eff(e_1, s_1, F) = \frac{0}{4} = 0.0 \qquad eff(e_1, s_2, F) = \frac{2}{2} = 1.0$$

We summarize the effectiveness of evasions across multiple scanners by computing the arithmetic mean of the effectiveness values across these scanners.

For the running example in Table 1, the evasion effectiveness for scanners $S = \{s_1, s_2\}$ is calculated as follows:

$$eff(e_1, \{s_1, s_2\}, F) = \frac{0.0 + 1.0}{2} = 0.5$$

$$eff(e_2, \{s_1, s_2\}, F) = \frac{\frac{2}{4} + \frac{2}{2}}{2} = 0.75$$

$$eff(e_{1,2}, \{s_1, s_2\}, F) = \frac{\frac{4}{4} + \frac{0}{2}}{2} = 0.5$$

Likewise, to summarize the effectiveness across a set of evasions, we average effectiveness values across the set. For the evasions $E = \{e_1, e_2, e_{1,2}\}$ in the example we have:

$$eff(\{e_1, e_2, e_{1,2}\}, \{s_1, s_2\}, F) = \frac{0.5 + 0.75 + 0.5}{3} \approx 0.58$$

Counter-effectiveness: attacker's cost of using evasions. Even though the goal of an evasion is to bypass the detection of a scanner, an evasion may also have the opposite effect: to cause a scanner mark a file as malicious that otherwise would be marked as benign. We call an evasion that has such an effect *counter-effective*.

DEFINITION 4 (EVASION COUNTER-EFFECTIVENESS). *Given a scanner s and a set F of malicious files, the counter-effectiveness of an evasion e is:*

$$counterEff(e, s, F) = \frac{|\{f \in F \mid \neg mal(s, f) \wedge mal(s, f^e)\}|}{|\{f \in F \mid \neg mal(s, f)\}|}$$

For example, for the evasions in Table 1 we have:

$$counterEff(e_1, \{s_1, s_2\}, F) = \frac{\frac{0}{0} + \frac{2}{2}}{2} = 0.5$$

$$counterEff(e_2, \{s_1, s_2\}, F) = \frac{\frac{0}{0} + \frac{0}{2}}{2} = 0.0$$

$$counterEff(e_{1,2}, \{s_1, s_2\}, F) = \frac{\frac{0}{0} + \frac{2}{2}}{2} = 0.5$$

From the attacker's perspective, another cost of using evasions is that they may interfere with the malicious behavior of a file. For example, an evasion in a PDF document that requires the user to move the mouse before the malicious behavior is triggered may not only hide the maliciousness but also reduce the chance that the attack is successful. One way of measuring this cost would be to conduct a user study that measures how often a file with an evasion successfully triggers the attack when the file is handled by users. We leave the challenge of measuring this cost for future work.

Added effectiveness by combining evasions. A set E of evasions that is combined in a file adds to the effectiveness of the individual evasions in E only if E is effective but none of the subsets of E are effective. We formalize this idea in the following metric.

DEFINITION 5 (EVASION ADDED EFFECTIVENESS). *Given a scanner s and a set F of malicious files, the added effectiveness of a combined evasion e is:*

$$addedEff(e, s, F) = \frac{|\{f \in F \mid mal(s, f) \wedge \neg mal(s, f^e) \wedge \nexists e' \subset e\ .\ \neg mal(s, f^{e'})\}|}{|\{f \in F \mid mal(s, f) \wedge \neg mal(s, f^e)\}|}$$

where $e' \subset e$ refers to the single or combined evasions that constitute e.

For example in Table 1, the added effectiveness of $e_{1,2}$, which is composed of e_1 and e_2, is:

$$addedEff(e_{1,2}, s_1, F) = \frac{2}{4} = 0.5$$
$$addedEff(e_{1,2}, s_2, F) = \frac{0}{0} = 0.0$$

Dependence of evasions on other components of a malware. To study how the effectiveness depends on other malware components, e.g., its payload or exploit, Definition 3 can be applied to subsets of all files that have that particular component in common. For example, to study how the effectiveness depends on the exploit used in a malicious PDF file, effectiveness is computed on the subset of all PDF files under study that are based on that very exploit. In Table 1, to focus on those files that use exploit x_2, we consider only the set of files F_{x_2} in rows 3, 4, 7, 8, 11, 12, 15, and 16. The effectiveness of evasion e_1 w.r.t. these files across all scanners is:

$$eff(e_1, \{s_1, s_2\}, F_{x_2}) = \frac{\frac{0}{2} + \frac{2}{2}}{2} = 0.5$$

The set of metrics defined above allows us to address the research questions given in Section 2.1. In particular, Definitions 1 and 2 address RQ1, Definition 3 addresses RQ2–3 and RQ6, Definition 4 addresses RQ4, and Definition 5 addresses RQ5.

3 CHAMELEON FRAMEWORK: GENERATING MALICIOUS, EVASIVE PDFS

Our study is based on various evasions, which we summarize in a taxonomy (Section 3.1). To systematically study how these evasions evade malware scanners, we present Chameleon, a framework to automatically create malicious files that contain one or more evasions. Our implementation of the framework focuses on malicious PDF documents. Such malware is particularly interesting because document-based malware attacks are a prevailing problem [3, 29, 52] and because the ability of PDF scanners to cope with evasions is currently understudied.

Figure 1 shows an overview of the Chameleon framework. The inputs to the framework are a set of evasions, a set of *exploits*, i.e., code that uses a bug or vulnerability, and a set of *payloads*, i.e., code that contains the malicious behavior of the attack. We discuss these inputs in Sections 3.1, 3.2, and 3.3, respectively. Given these inputs, Chameleon generates evasive PDF documents and validates that they still behave maliciously despite the evasion(s). We then pass these documents to a set of PDF scanners (Section 4) and measure their ability to handle the evasions (Section 5).

3.1 Evasions

Various evasion techniques, for executables and other potentially malicious file formats have been proposed [1, 16, 22, 35, 39, 42, 53, 69]. To provide some background on different kinds of evasions and the scope of this work, we present a taxonomy of evasions. The taxonomy tries to cover the major classes of evasions that are relevant for malicious documents without claiming to be complete. In particular, we focus on evasions implemented in high-level languages

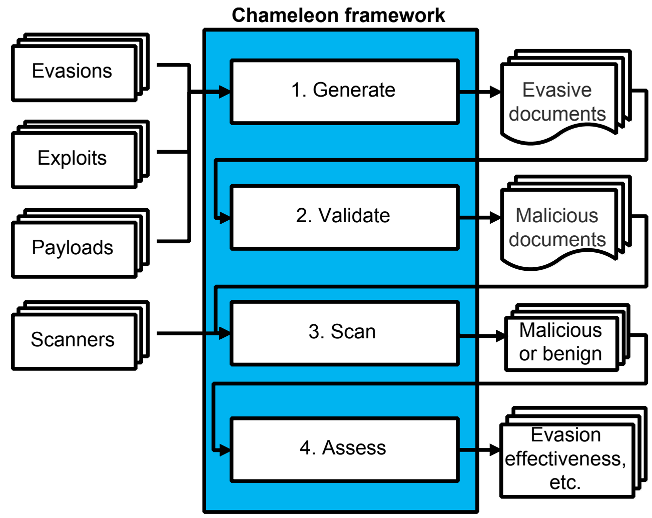


Figure 1: Overview of the Chameleon framework and its four steps.

that can be embedded into document formats, such as JavaScript and Visual Basic.

Figure 2 shows an overview of the taxonomy. We distinguish between dynamic and static evasions. *Static evasions* attempt to modify the document or the code embedded into it in a way that influences a static analysis of the document. In contrast, *dynamic evasions* change the run-time behavior of a document to influence the outcome of a dynamic analysis of the document.

3.1.1 Static Evasions. Among the static evasions, there are two broad classes. First, *run-time loading* tries to conceal malicious behavior by loading parts of the code at run-time, making it harder for a static scanner to detect the maliciousness. For example, an evasion based on run-time loading may download the malicious payload once the document is opened on the victim's machine, i.e., after having been checked by a static scanner. Second, *obfuscation* modifies the malicious source code to conceal its purpose. There are various obfuscation techniques, such as encryption, multi-pass encoding, logical xor, and changing the code structure [35].

3.1.2 Dynamic Evasions. Dynamic evasions can be broadly classified into three categories. The first category are *environment-based evasions*, which attempt to take the execution environment into account. This approach is specially appealing for targeted attacks, where the attacker has some information about the target system. We further classify environment-based evasions into the following five categories:

Network. Dynamic scanners may restrict the network access of documents to prevent malware from downloading its payload. Network-based evasions check the network connection to identify the presence of a dynamic scanner or a sandbox.

File system. Since many dynamic scanners rely on known libraries or executables, the presence of particular files in the file system may disclose a dynamic scanner. File system-based evasions check whether particular files exist to decide whether to perform any malicious behavior.

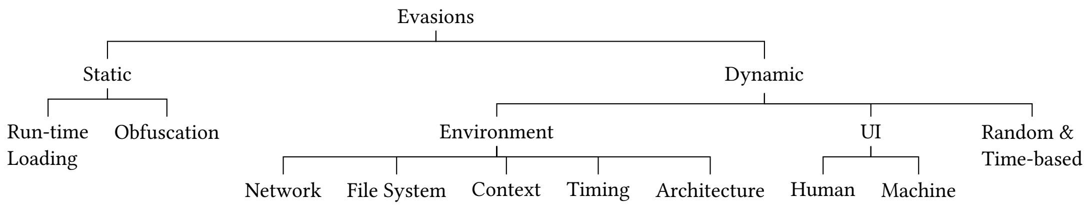


Figure 2: A taxonomy of evasion techniques.

Context. Information about the system language, locales, most recently used documents, the time zone, etc. can be abused by attackers to target particular victim systems [43, 58]. A context-based evasion deceives dynamic scanners by behaving maliciously only in particular contexts.

Timing. Due to the virtualized environment used by most dynamic scanners, some operations have observably lower performance than other operations. For example, the performance difference of a CPU-intensive computation and a GPU-intensive computation is higher in a virtual machine than on a physical machine. The reason is that in a modern virtual machine, many CPU instructions run natively, whereas translating GPU instructions to physical instructions imposes a noticeable overhead [33]. Timing-based evasions exploit such differences in execution time to determine the presence of a dynamic scanner [7].

Architecture. These evasions recognize architectural idiosyncrasies of the underlying physical or virtual machine. Examples include an incorrectly return value of the `CPUID` instruction in QEMU [25] and GPU fingerprinting [11].

The second category of dynamic evasions are *UI-based evasions*. Such evasions monitor interactions with UI elements to determine whether a human or a machine is using the system. We further classify UI-based evasions into two sub-classes:

Human user. These evasions attempt to identify a human user and expose the malicious behavior only to such users. For example, an evasion may wait until the user scrolls to a particular page or clicks a particular UI element [70].

Machine user. Instead of trying to detect a human user, an evasion may also check for evidences that a machine is interacting with the system. For example, text entered into a form with a superhuman typing speed or clicks on an invisible element suggests the presence of a machine user [37].

The third category of dynamic evasions are *random-based and time-based evasions*. This kind of evasion triggers an attack either probabilistically or depending on the current time, e.g., only on specific times of the day [17].

3.1.3 Implementation of Evasions. Based on our taxonomy, we have implemented 19 evasions (7 static and 12 dynamic), as summarized in Table 2. Some evasions take an argument to configure different variants of the evasion. For example, the "lang" evasion can be configured by passing the language to check for, and the "delay" evasion can be configured with a specific amount of time. Using the "lang" evasion with "English" as the argument will result in a document that attacks only computers with the English version of Adobe Reader:

```
if (app.language == "English")
    exploit(); // trigger the exploit
```

In addition to injecting individual evasions into documents, Chameleon also allows to blend multiple evasions into *combined evasions*. We refer to combined evasions that contain at least one static and at least one dynamic evasion as *hybrid evasions*. When combining evasions of the same kind, we focus on evasions from different classes, e.g., run-time loading with JavaScript obfuscation. For UI-based evasions, we also combine several evasions from the same class to gradually increase the complexity of the UI interactions required to trigger the attack. Moreover, Chameleon creates an evasion that combines several context-based evasions, to create a document that targets a very specific environment and remains silent otherwise.

3.2 Exploits

Chameleon uses two PDF exploit modules provided by the Metasploit framework[1] and adapts them to introduce evasions. The "Toolbutton" exploit[2] abuses a use-after-free vulnerability in the implementation of the Adobe-specific JavaScript function `app.addToolButton`. The exploit executes some JavaScript code to set up the environment and then triggers the vulnerability by calling the vulnerable function. To implement dynamic evasions, we trigger the vulnerability only if the condition checked by the evasion holds.

The "Cooltype" exploit[3] uses a malicious font file in addition to malicious JavaScript code. The font file is loaded after the JavaScript code has set up the environment for exploitation. We slightly modify the exploit by adding an exploitation trigger that controls whether and when the exploit is executed. The dynamic evasions call this trigger only if the condition checked by evasion holds.

In addition to "Toolbutton" and "Cooltype", Metasploit provides other PDF exploit modules. We choose these two exploits as they target a popular PDF reader software (Adobe Reader) and because they are old and well-known. If our evasions can fool PDF scanners using old and well-studied exploits then the evasions are at least as or even more effective when applied to more recent or zero-day exploits.

3.3 Payloads

Another important component of any attack is the payload that it carries. As payloads, Chameleon uses native machine code that is executed after the vulnerability is triggered. We use three different payloads, two provided by Metasploit and one that we develop ourselves. The first payload, "Reverse Bind", establishes a TCP

[1] https://github.com/rapid7/metasploit-framework
[2] CVE-2013-3346
[3] CVE-2010-2883

Table 2: Static and dynamic evasions implemented in the Chameleon framework. The last column denotes whether the evasion is implemented in the PDF structure, the embedded JavaScript code, or both.

Class	Name	Description	Implementation
Static evasions:			
Run-time loading	steganography	Encode the JavaScript code into an image file embedded in the PDF document. Load and `eval` the code at run-time.	PDF & JavaScript
	content	Store the JavaScript code as the content in the PDF document. Load and `eval` the code at run-time.	PDF & JavaScript
JavaScript obfuscation	rev	Lexically reverse the JavaScript code.	JavaScript
	xor	Encode the JavaScript code by applying the bitwise xor operator with the specified key.	JavaScript
PDF obfuscation	objstm	Compress the malicious PDF as an Object Stream and put it into a benign PDF document.	PDF
	nest	Recursively embed the malicious PDF into a benign PDF document for one or more times.	PDF
	decoy	Insert the malicious JavaScript code into a benign PDF document. In contrast to "nest", this evasion does not recursively nest documents into each other.	PDF
Dynamic evasions:			
Context	lang	Trigger if the language of the PDF viewer is in the specified set of languages.	JavaScript
	resol	Trigger if the desktop resolution is in the specified range.	JavaScript
	mons	Trigger if the user's computer has the specified number of monitors attached to it.	JavaScript
	filename	Trigger if the generated exploit's filename has not changed. Some scanners change the filename before the analysis.	JavaScript
UI	scroll	Trigger when the user has scrolled to the specified page.	PDF
	captcha	Trigger if the user's text input matches the specified string.	JavaScript
	alert_three	Show an alert dialog box with three buttons and trigger if the specified button is clicked.	JavaScript
	doc_close	Trigger when the document gets closed.	PDF
	alert_one	Show an alert dialog box with one button and trigger when the button is clicked.	JavaScript
	mouse	Trigger if the mouse position changes.	JavaScript
Random and time-based	delay	Delay the exploitation for the given amount of time (time bomb).	JavaScript
	tod	Trigger at the specified time of the day.	JavaScript

connection to a remote host allowing the remote host to control the exploited machine. The second payload, "Powershell", spawns an instance of Windows Powershell with a command that creates a text file in a temporary directory. The third payload, "Exit", simply exits the Adobe Reader process.

3.4 Generating and Validating Evasive Documents

We implement the Generate step of Chameleon on top of the Metasploit framework, which we use to generate exploit documents, and the Origami PDF transformation library[4], which we use to manipulate documents. The 19 evasions are implemented as a new Metasploit module, which can be used with any of the PDF exploit modules.

After generating a supposedly malicious document, Chameleon checks that the document is indeed malicious (step Validate). To this end, Chameleon opens the document in the vulnerable version of Adobe Reader inside a sandbox, interacts with it according to the evasions (e.g., by moving the mouse or waiting for some time), and checks whether the payload is executed. At the moment this process is mostly but not fully automated because for context-based evasions, the sandbox needs to be manually adapted to the context that an evasion is looking for (e.g., for the "mons" evasion, the number of displays attached to the sandbox has to be properly set).

Our implementation and a set of 1,395 generated PDF documents are publicly available.[5]

4 PDF SCANNERS

We study 36 static and 5 dynamic scanners, including both academic and widely used commercial tools, as listed in Table 3. To categorize a scanner as static or dynamic we rely on information provided by the vendors or developers. Based on this information, we consider a scanner as static if it reasons about a PDF document without opening the document in a PDF viewer. In contrast, dynamic scanners open a PDF document in a PDF viewer or an emulator and then analyze its runtime behavior, e.g., by tracking how the PDF viewer interacts with the operating system. Our study includes more static than dynamic scanners because static scanners are more common in practice.

To run the commercial static scanners on our PDF documents, we use the application programming interface (API) of VirusTotal that runs close to 60 static scanners at once on a given document. We ignore those scanners that do not detect any of the exploits we use (perhaps because they are not designed to detect PDF malware), which leaves 34 commercial static scanners. To run the commercial dynamic scanners, we use the individual APIs provided by the respective vendors of these scanners. The vendors of two commercial dynamic scanners requested to participate anonymously, so we refer to them as DS1 and DS2. Appendix A.1 explains the detailed setup of the non-commercial scanners. In addition to the

[4]https://github.com/gdelugre/origami

[5]https://github.com/sola-da/Chameleon/

Table 3: PDF scanners used for the study.

Scanner	Static	Dynamic	Academic	Commercial
ALYac	✓			✓
AVG	✓			✓
AVware	✓			✓
Ad-Aware	✓			✓
AhnLab-V3	✓			✓
Antiy-AVL	✓			✓
Arcabit	✓			✓
Avast	✓			✓
Avira	✓			✓
Baidu	✓			✓
BitDefender	✓			✓
CAT-QuickHeal	✓			✓
Cuckoo		✓	✓	✓
Cyren	✓			✓
DS1		✓		✓
DS2		✓		✓
Emsisoft	✓			✓
F-Prot	✓			✓
F-Secure	✓			✓
Fortinet	✓			✓
GData	✓			✓
Ikarus	✓			✓
Jiangmin	✓			✓
Kaspersky	✓			✓
MAX	✓			✓
McAfee-GW-Edition	✓			✓
MicroWorld-eScan	✓			✓
Microsoft	✓			✓
NANO-Antivirus	✓			✓
PDF-Scrutinizer [61]		✓	✓	
Qihoo-360	✓			✓
Rising	✓			✓
SAFE-PDF [36]	✓		✓	
Slayer [47]	✓		✓	
Sophos	✓			✓
SploitGuard		✓		✓
Symantec	✓			✓
Tencent	✓			✓
TrendMicro	✓			✓
VIPRE	✓			✓
ZoneAlarm	✓			✓

scanners listed in Table 3, we considered several others, including PDFRate [63] and PJScan [41], but were unable to use them for our study because they either were unavailable or had some issues in our local setup (see Appendix A.2 for details).

5 RESULTS

In this section, we address the research questions from Section 2.1 by applying the methodology from Section 2.2. We apply 41 widely used PDF scanners to a total of 1,395 malicious PDF documents generated by the Chameleon framework and an additional 81 benign PDF documents. The benign documents comprise train tickets, governmental documents, manuals, tutorials, and some suspicious looking PDF files that are known to be benign. All documents used for our study will be made available as a benchmark for future work.

5.1 RQ1: Recall and False Positives

The following addresses RQ1, i.e., how accurately the scanners classify documents into malicious and benign in the presence of evasions. We measure the recall and the false positive ratio of each scanner, as described in Section 2.2. Figure 3 shows the results. A higher recall means that the scanner is more successful in identifying malicious PDF documents, despite the presence of evasions. The figure shows that almost all studied scanners are affected by evasions, as their recall values are lower than 100%. Furthermore, we find a huge variation across the studied scanners: While some scanners, e.g., SAFE-PDF and AVG, identify all or most malicious documents despite evasions, others miss many malicious documents. Some scanners have a recall lower than 20%, showing that they are easily bypassed by evasions.

In principle, a scanner could achieve 100% recall by labeling each document as malicious. To address this potential problem, Figure 3 also shows the false positive ratio of each scanner. We find that all scanners have a false positive ratio below 15%, except Cuckoo (17.5%), Slayer (28.77%), and SAFE-PDF (34.57%). There is no strong correlation (Pearson correlation coefficient: 36.61%) between recall and false positive ratio. We conclude from these results that none of the scanners tries to boost its recall at the cost of precision, which seems reasonable as users easily drop a tool if they are overwhelmed with spurious warnings.

5.2 RQ2: Evasion Effectiveness by Scanner

To better understand the susceptibility of the scanners to static and dynamic evasions, we assess the effectiveness of evasions in bypassing specific scanners (RQ2). We compute the evasion effectiveness for each scanner by averaging the effectiveness across all evasions. Figures 5a and 5b present the results for static and dynamic evasions, respectively. A lower value indicates that a scanner is less susceptible to evasions. The results for the static evasions in Figure 5a show some interesting effects. Somewhat surprisingly, the effectiveness of 12 of the 34 VirusTotal scanners, roughly in the middle of the figure, is exactly the same, out of which 8 have the exact same recall, too (Figure 3). A possible explanation is that multiple scanners rely on the same underlying decision mechanism, e.g., because one scanner queries another scanner as part of its decision, or because the same analysis algorithm is provided under several brands. Previous, informal reports claim that some static scanners share their results [67], which our results confirm.

Another interesting observation is that a dynamic, not a static, scanner (DS2) is the most susceptible to static evasions. A comparison of Figures 5a and 5b shows that DS2 is highly susceptible to both dynamic and static evasions. This finding suggests that DS2 not only uses dynamic analysis, but also heavily relies on static analysis techniques.

The static scanners in the right part of Figure 5b are impacted by dynamic evasions. A likely reason is that adding an evasion changes the signature of the PDF documents, and that the scanners rely on these signatures.

5.3 RQ3: Most Effective Evasions

Understanding which evasions are most effective (RQ3) is important both for attackers and for developers of security scanners. We measure the effectiveness of evasions for each scanner and then compute the average over all static and the average over all dynamic scanners. Some evasions take arguments, e.g., the language used by the “lang” evasion or the xor key used by the “xor” evasion. For such evasions, we try a range of arguments and report the highest observed effectiveness.

Figure 4 shows the results. We sort the evasions as in Table 2. Overall, the results show that static scanners are much more susceptible to static evasions, while dynamic scanners get fooled by dynamic evasions, which is unsurprising and confirms our classification of evasions.

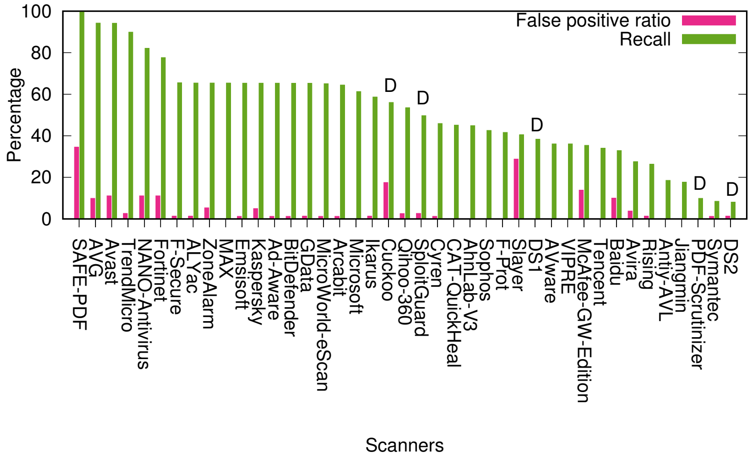


Figure 3: Recall and false positive ratio of the studied scanners. The dynamic scanners are marked with "D".

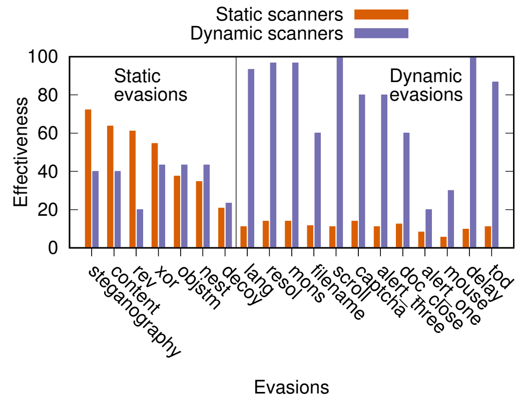


Figure 4: Effectiveness for different classes of static and dynamic evasions. The results are averaged over all static (red) and dynamic (blue) scanners.

Table 4: The evasions that bypass all but two scanners. The evasions are applied to a document in the given order.

	Combined evasions
1	mouse, scroll, content, steganography, xor (key: 40)
2	alert_one, scroll, content, steganography, xor (key: 40)
3	alert_three (trigger on No or Cancel), mouse, mons (>1), filename, lang (German), tod (8 AM – 4 PM), scroll, content, steganography, xor (key: 40)

Among the static evasions, those related to run-time loading and JavaScript obfuscation are the most effective, suggesting that many static scanners rely on checking the JavaScript code embedded into PDFs to identify malicious behavior. The high effectiveness of many of the static evasions is somewhat surprising given that some of these static evasions have been known for several years [16, 21, 22].

For dynamic evasions, attackers can choose from a relatively large set of highly effective evasions, including the two time-related evasions, most of the context-related evasions, and some of the user interaction-related evasions, e.g., "scroll". In contrast, some other UI-related evasions are only moderately effective, e.g., "mouse". The reason is that some of the dynamic scanners use anti-evasion techniques, such as user interaction emulation, to counter these evasions. For example, Cuckoo moves the mouse after opening a document in a PDF reader to counter the "mouse" evasion [30].

To better understand highly effective evasions with their particular arguments across all scanners, Table 4 lists the evasions that bypass all but two scanners (NANO-Antivirus and SAFE-PDF) for at least one exploit. All the evasions presented in Table 4 are hybrid, showing that combinations of static and dynamic evasions are effective as they bypass both static and dynamic scanners at the same time. Overall, the observation that three different combinations of evasions can circumvent almost all scanners is alarming and motivates future work on anti-evasion techniques.

5.4 RQ4: Counter-effective Evasions

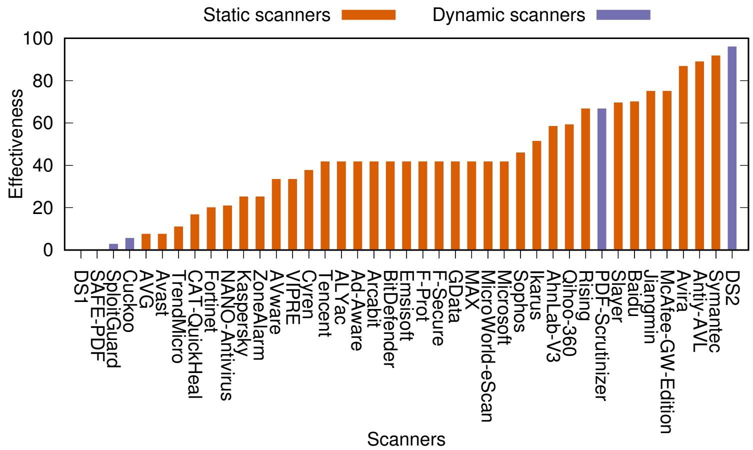
In the following we address RQ4, i.e., whether some evasions have the opposite of the expected effect by causing a scanner to detect an otherwise missed malicious document. To answer the question, we measure the counter-effectiveness of each evasion for each scanner and then compute the average over all static scanners and the average over all dynamic scanners. For evasions that take parameters, we report the highest counter-effectiveness observed across a range of values.

Figure 7 shows the counter-effectiveness of the studied evasions, sorted as in Figure 4. Perhaps surprisingly, most evasions are, at least sometimes, counter-effective. A likely reason is that some scanners consider the changes of the document caused by the evasions as indicators of malicious intent. For example, the context-related evasions add some code to the document to check the current context, and some scanners may consider this activity to be suspicious. In fact, all context-related and time-related evasions are counter-effective. Furthermore, all evasions are counter-effective for at least some static scanners, with the exception of the "steganography" evasion. This evasion's high effectiveness (Figure 4) and low counter-effectiveness should concern the developers of scanners.

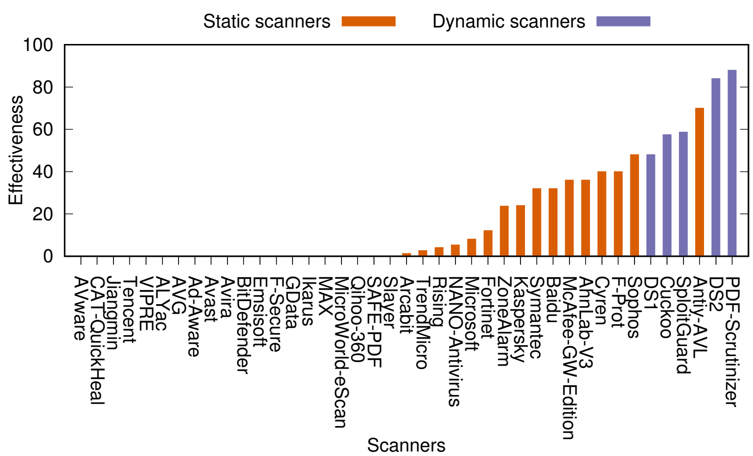
Although most evasions are sometimes counter-effective, the counter-effectiveness in Figure 7 is relatively low compared to the effectiveness of evasions. Moreover, we observe counter-effectiveness only in a relatively small subset of the studied scanners. For static scanners, the evasions behave counter-effectively only on McAfee-GW-Edition, Qihoo-360, and Rising. For dynamic scanners, all counter-effective behavior that we observe is due to DS2.

5.5 RQ5: Combinations of Evasions

A combination of evasions may be more effective than the individual evasions. For example, even though some evasions may not be able to bypass a scanner alone, their combination may be able to do so (RQ5). In the following we discuss the added effectiveness of combined dynamic, combined static, and hybrid evasions. Figure 8 presents the results for combined evasions with more than 0.5%

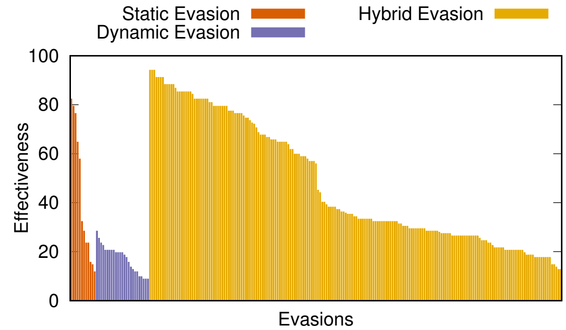


(a) Static evasions

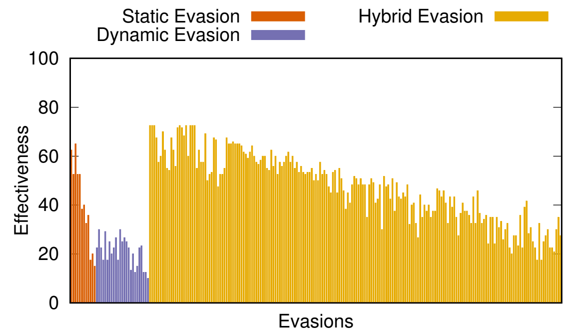


(b) Dynamic evasions

Figure 5: Per-scanner effectiveness of static and dynamic evasions.



(a) Documents with "Toolbutton" exploit.



(b) Documents with "Cooltype" exploit.

Figure 6: Effectiveness of evasions for the subsets of malicious documents that use a specific exploit. Each bar corresponds to an evasion with a specific argument. The hybrid evasions, and some of the static and dynamic evasions result from combining evasions (Section 3.1.3).

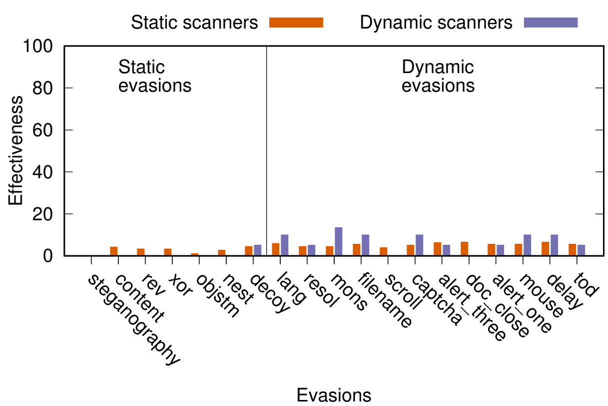


Figure 7: Counter-effectiveness for different classes of static and dynamic evasions. The results are averaged over all static (red) and dynamic (blue) scanners.

added effectiveness. Averaged over all scanners, the added effectiveness of even the most successful combined evasions is relatively low (about 3.2%). For some individual scanners, though, we find higher added effectiveness values. That is, an attacker interested in bypassing a particular scanner could combine evasions suitable for this task.

Interestingly, combining multiple static evasions does not cause any added effectiveness, suggesting that a single static evasion is sufficient to fool scanners susceptible to this kind of evasion. Furthermore, all combined dynamic evasions in Figure 8 result from combining UI-based evasions, showing that an evasion that requires a more complicated user interaction is more successful.

5.6 RQ6: Influence of Exploits and Payloads on Evasion Effectiveness

The effectiveness of an evasion may depend on the specific exploit or payload used in a malicious document. For example, consider an

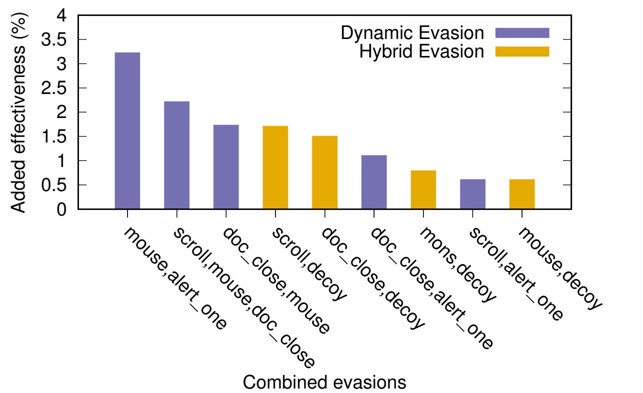


Figure 8: Evasions that have greater than 0.5% added effectiveness.

exploit that relies on malicious JavaScript and therefore may be detected by scanners that check the JavaScript code in a document. For such an exploit, a JavaScript-based evasion may work particularly well, because the evasion reduces the chance that scanners identify the document as malicious. The following studies to what extent the effectiveness of an evasion depends on the exploit or payload used in the malicious document (RQ6). To this end, we compute the effectiveness of each evasion for the subset of all documents that use a particular exploit or payload.

5.6.1 Influence of Exploit. Figure 6a shows the evasion effectiveness for documents with the "Toolbutton" exploit. The evasions related to JavaScript obfuscation work particularly well, since this exploit is based on malicious JavaScript code only, i.e., no other objects, such as fonts or images, are needed. Many of these evasions are greater than 80% effective. The sudden drop in the effectiveness of static and hybrid evasions is also due to the drastically higher success of JavaScript obfuscation-based versus PDF obfuscation-based evasions.

The evasion effectiveness for documents based on the "Cooltype" exploit is shown in Figure 6b. We use the same order of evasions as in Figure 6a to enable a comparison between the two exploits. The results show several interesting effects. First, the most effective evasions for the "Toolbutton" exploit reach almost 100% effectiveness, whereas the peak effectiveness of "Cooltype"-based documents is only around 75%. The reason is that "Cooltype" requires both malicious JavaScript code and a malicious font file to be embedded in the PDF. As a result, none of the static evasions alone is highly effective at hiding "Cooltype"-based documents. Second, the effectiveness of evasions based on PDF obfuscation are higher for "Cooltype" than for "Toolbutton" (the second half of static evasions' bars in the figure). This result suggests that many scanners identify the exploit by searching for the malicious font file and thereby make those evasions effective that change the signature of the PDF document (and hence the signature of the embedded font file).

5.6.2 Influence of Payload. With the same approach as exploits, we study the dependence of the evasions on the payload. We compute the effectiveness of the subset of the samples with each of the three payloads. In contrast to the exploits, we do not observe any major differences in effectiveness of the evasions.

Overall, studying the influence of exploits and payloads on the effectiveness of evasions shows that exploits and evasions may influence each other. Developers of PDF scanners should be aware of this influence when developing anti-evasion techniques, as an attacker might choose suitable evasions depending on how a PDF exploit works.

6 DISCUSSION

In this section, we discuss how security scanners can defend against evasions (Section 6.1) and what limitations our work currently has (Section 6.2).

6.1 Mitigating Evasions

One way to mitigate dynamic evasions is to adapt general anti-evasion techniques from other domains to the problem of analyzing PDF documents. Several recent papers propose to load a potentially malicious file in environments targeted at revealing the malicious behavior of the file. For example, FuzzDroid [58], IntelliDroid [73], and SmartDroid [79] try to cause a potentially malicious Android app to reach "sensitive" API calls that would reveal malicious behavior, such as sending an SMS to a premium number. Adapting this technique to PDF scanners requires identifying sensitive APIs in PDFs. For known exploits, such APIs may be known, e.g., it is known that the "Toolbutton" exploit relies on calling the `app.addToolButton` API. Finding sensitive APIs for previously unknown exploits remains an open research problem. A related technique to cope with dynamic evasions is to explore multiple execution paths for branch decisions that depend on the environment in which a file is executed. Rozzle [40] proposes this idea for client-side JavaScript code. Adapting their approach is a promising direction for mitigating the environment-related dynamic evasions.

To deal with UI-related evasions, dynamic scanners could adapt ideas used in PuppetDroid [27] and PyTrigger [26]. These approaches record an interaction trace from a human and play it back when loading the file under analysis to get through possible checks that guard the attack. One of the dynamic scanners studied in this work, Cuckoo, mitigates evasions using a simpler form of this idea: The scanner arbitrarily moves the mouse to simulate a human user [30]. However, this mitigation technique is unlikely to work for evasions that require a more complicated user interaction, such as a "captcha".

To identify files that behave differently in an analysis environment, some techniques compare the execution behavior of the file in several different environments, e.g. virtual and physical [6]. Another kind of anti-evasion technique is to hide any difference between a virtual and a physical execution environment to fool the evasive malware [62]. Finally, to deal with the large number of possible evasions and combinations of evasions, training machine learning models to distinguish benign from malicious files seems to be a worthwhile direction [16, 41, 63, 65]. The main challenge for effectively training machine learning models is to obtain a sufficiently large set of labeled data. Our framework could serve as a generator of malicious training files that use different evasions and combinations of evasions.

The high recall of SAFE-PDF [36], which is based on abstract interpretation of JavaScript code embedded in PDFs, shows that conservative program analysis may provide an effective way of detecting malicious behavior despite evasions. The downside of any conservative program analysis are spurious warnings, which the relatively high false positive ratio of SAFE-PDF confirms.

6.2 Choice of Scanners

We focus on in-production, commercial security scanners because they represent the current state-of-the-practice, and recent academic scanners because they represent the state-of-the-art. The studied scanners contain more static than dynamic scanners because static scanners currently dominate the market. For example, the VirusTotal service aggregates more than 60 static scanners at the time of writing this paper [2], whereas we could find only ten commercial dynamic scanners, out of which three consented to participate in this research.

Our work should not be understood as a comparison of different scanners, but rather as a comparison of each scanner's effectiveness before and after adding evasions. The version of the scanners used in online aggregation services, which we use for the studied static scanners, may differ from the full-fledged scanners, because vendors may optimize the response time for an online service [56].

7 RELATED WORK

Studying Evasions. Previous work has studied to what extent evasions help in circumventing scanners for malware types other than PDF. These studies consider Android [10, 23, 24, 55, 59, 80], Windows executables [14, 49], and JavaScript [76]. Their measurements focus on reporting for each evasion whether the scanners could still detect a malicious file. Our work differs both in the methodology and in its application. Methodologically, our study goes beyond a single binary measure and answers additional questions, such as the added effectiveness of combined evasions and the dependence of evasions on other malware components, e.g., the payload. Regarding the application, this work is the first to provide an in-depth study of the effectiveness of evasions for PDF-based malware.

Analysis of PDF Malware. Non-executable document formats, such as PDF, have become one of the main vectors for delivering malware to victims [32]. To detect PDF documents that contain malicious JavaScript code, combinations of static and dynamic analysis of the embedded JavaScript code search for suspicious operations that rarely occur in benign documents [44, 45, 61, 68]. Another line of work statically extracts features of documents, e.g., based on a document's metadata and structure [47, 63, 65] or based on embedded JavaScript [16, 41], and then trains a machine learning model to identify malicious documents. Nissim et al. survey these and other techniques [51]. Beyond PDFs, the problem of malicious documents extends to other document formats [50]. A recurring problem for all document scanners is how to evaluate them, particularly, in the presence of evasions. Chameleon provides a generic mechanism to create malicious documents beyond well-studied sets of documents, such as the Contagio malware dump[6].

JavaScript Analysis. Malicious PDF documents contain malicious JavaScript code. Identifying such code has been actively researched for client-side web applications, by analyzing potential malware samples in a sandbox [72], through learning-based anomaly detection [18], by classifying abstract syntax trees [19], or by searching for malicious sites with specially crafted search engine queries [34]. A recent survey discusses various other security-related analyses of JavaScript code [4]. All these approaches focus on JavaScript code in web applications, which differs from JavaScript code embedded in PDF documents.

From Logic Bombs to Modern Evasions. Attempts to fool detectors of malicious software are probably as old as malicious software itself. Earlier approaches use logic bombs, where an attack is initiated upon occurrence of an external event [5, 28]. To counter malware scanners that execute a potentially malicious file in a virtualized environment, anti-virtualization techniques have been proposed [57]. Chen et al. [13] provide a taxonomy of malware evasion techniques with a focus on anti-virtualization and anti-debugging behavior. Some of the evasions studied in this paper can be used to detect a virtualized environment, while others, e.g., the UI evasions, can also detect scanners running on a physical machine. Transparent scanners try to mimic a real execution platform, i.e., without any traces of virtualization or specific fingerprints [38], but even those can be evaded via evasion techniques that check the system's past use, e.g., via the Windows registry size or the total number of browser cookies [48]. Several survey articles discuss other evasion techniques [9, 15], including code transformation techniques similar to our obfuscation evasions [77].

Evasions in Document-based Attacks. We envision future work to extend our framework with additional evasions, e.g., PDF parser confusion attacks [12]. Other recent evasion techniques fool machine learning-based scanners, for instance by slightly modifying a benign document [46] or by stochastically modifying a malicious document [20, 75]. Knowing that attackers might conceal malicious behavior through evasions, Zhang et al. [78] propose an approach to improve machine learning-based scanners through adversary-aware feature selection. Finally, there are two previous papers that systematically study the effectiveness of evasions. Biggio et al. [8] study to what extent learning-based malware classifiers can be fooled by evasions. In contrast, we do not make any assumptions about the studied scanners and (probably) include both learning-based and not learning-based scanners. Laskov et al. [66] focus on a single scanner (PDFRate), whereas our study involves 41 scanners.

8 CONCLUSION

This paper presents a methodology to evaluate the effectiveness of evasions and its application to studying PDF malware scanners. Our implementation of the methodology, the Chameleon framework, automatically generates and enriches malicious documents with one or multiple evasions. We use these documents for an in-depth study of 41 PDF scanners and how they are affected by evasions. More broadly, our methodology can also be used for studying evasions of other malware types, e.g., malicious executables.

The overall result of our study is cause for concern. We show that the studied evasions are surprisingly effective in fooling state-of-the-art scanners. In particular by combining evasions, attackers can bypass modern defenses in both static and dynamic scanners.

[6] http://contagiodump.blogspot.com/

Moreover, we find huge variations across scanners, enabling targeted attacks based on evasions picked specifically for a targeted scanner. All these findings are a call to arms for future work on anti-evasion techniques.

Our work will support future efforts toward improving malware scanners in several ways. First, the results of our study help security vendors to better understand their vulnerability to specific evasions and to focus their attention on mitigating the most effective evasions. Second, we are releasing the corpus of malicious, evasive documents generated by Chameleon as a ready-to-use benchmark. We are in contact with several developers of PDF scanners, and some of them, e.g., SploitGuard and SAFE-PDF, have already used our benchmark to test and improve their security scanners. Finally, the Chameleon framework provides a basis for expanding the set of benchmarks by incorporating future evasions, exploits, and payloads.

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A DETAILS ON PDF SCANNERS

A.1 Setup of Academic and Open-Source Scanners

The following describes the academic and open-source scanners, i.e., Slayer, SAFE-PDF, PDF Scrutinizer, and Cuckoo Sandbox, and how we set them up for our study. In addition, we briefly go through the internals of SploitGuard, which, even though a commercial scanner, is based on an academic work [54].

Slayer [47], also known as PDF Malware Slayer or PDFMS, is a machine learning-based static scanner. It predicts whether a document is malicious based on the document's internal structure. We train Slayer with a set of malicious and benign PDF files that are obtained from Mila Parkour, the owner of Contagiodump[7], a public malware repository. The malicious sets comprises more than 11,000 files, which are labeled as 'MALWARE_PDF_CVEsorted_173_files' and 'MALWARE_PDF_PRE_04-2011_10982_files'. The benign set comprises 9,000 files labeled as 'CLEAN_PDF_9000_files'.

SAFE-PDF statically reasons about a file based on abstract interpretation. It is designed to cope with malicious PDF documents that incorporate evasions. By abstract interpretation, it over-approximates the run-time behavior of a document to examine all its possible execution paths.

PDF Scrutinizer [61] extracts all JavaScript code snippets from a PDF document, executes the code in Mozilla Rhino, and uses libemu to find and analyze the payload. The tool combines both static and dynamic analysis techniques, but as more weight is put on the dynamic part, we classify it as a dynamic scanner.

Cuckoo Sandbox [31] (in short Cuckoo) scores each analyzed sample on a scale of 0 (benign) to 10 (certainly malicious). To map this score into a binary score (malicious or not), which is necessary to compare Cuckoo with other scanners, we set a threshold on the score reported by Cuckoo. To this end, we scan documents with the bare exploits, i.e., without any evasion, with Cuckoo and take the minimum score among them, 3.0, as the maliciousness threshold. We consider any score greater than or equal to this threshold as a "malicious" classification, and any score smaller than the threshold as "benign". We evaluate Cuckoo out-of-the-box with no additional extensions installed, except Cuckoo Signatures[8], which are community rules that assign score to observed behaviors (e.g., dropping executable files). We configure Cuckoo's guest machine with two processors, 2 GB of memory, and one virtual monitor having 720p resolution (important for "mons" and "resol" evasions). The guest machine runs Windows 7, 64-bit, and has Adobe Reader 9.0, the version vulnerable to our exploits, installed.

SploitGuard is a dynamic scanner based on Lockdown [54] that detects the exploitation of vulnerabilities by enforcing different policies during the execution of a program, for example Adobe Reader. By design, SploitGuard does not need to be trained, and the result for a given document is a binary decision "malicious" or "benign".

[7] http://contagiodump.blogspot.com/

[8] https://github.com/cuckoosandbox/community/

A.2 Other Considered Analyzers

We considered several other academic scanners but could not include all of them, because some are either not available or have some issues in our local setup. The following is a list of scanners that we considered but unfortunately could not include in our study.

- PDFRate [63]: A learning-based PDF scanner that decides whether a document is malicious based on its structure. PDFRate's online service[9] was not available at the time of writing this paper.
- MDScan [68]: Combining static and dynamic analysis, MDScan specifically targets PDF files. The dynamic analysis is via extracting JavaScript snippets and running them on an emulator. The source code for MDScan is not available in the public domain.
- Lux0r [16]: A machine learning approach aimed at detecting malicious JavaScript code in general, but evaluated with malicious JavaScript-bearing PDF documents. By tapping into the JavaScript interpreter, Lux0r anticipates a malicious behavior based on the API usage. Lux0r is not publicly available.
- MPScan [45]: MPScan extracts and de-obfuscates the JavaScript code on the fly by hooking into Adobe Reader, and then statically analyzes it to detect a malicious behavior. MPScan's source code is not publicly available.
- ShellOS [64]: Even-though designed mainly for executable files, ShellOS can find the payload in a malicious PDF document and analyze it too. However, the tool is not publicly available.
- The tool by Carmony et al. [12]: To improve the detection accuracy, Carmony et al. improve extraction of the JavaScript snippets of a PDF document. The tool then uses PJScan [41] for classification of the extracted snippets. The tool is not publicly available.
- CWXDetector [71]: By disabling data execution prevention (DEP), CWXDetector monitors the execution of code from non-executable pages (former exploits usually tried to execute code from the heap, which is non-executable). Once such a write happens, the page fault handler is invoked and the page's content is dumped for further analysis. CWXDetector can be used for several file types such as executable and PDF files. However, it is not available online.
- Tool by Liu et al. [44]: By statically instrumenting a document to insert context-monitoring code, the instrumented document's behavior is observed at run-time. The tool is not publicly available.
- PJScan [41]: A static scanner that uses machine learning to detect malicious files. We tried to train PJScan[10] with the same sets of files used for training Slayer, but unfortunately, it did not find any JavaScript code (even though most of the files contain embedded JavaScript). Therefore it could not be trained and evaluated in our setup.
- PlatPal [74]: Runs a PDF document in Adobe Reader and track its behavior on Windows and macOS. Based on the discrepancies in the execution traces (e.g. the amount of dynamically allocated memory), it marks the document as either malicious or benign. We hit compilation errors while trying to build the tool[11] locally and unfortunately the documentation did not help us to resolve them.

[9] https://csmutz.com/pdfrate/

[10] https://sourceforge.net/p/pjscan/home/Home/

[11] https://github.com/sslab-gatech/platpal