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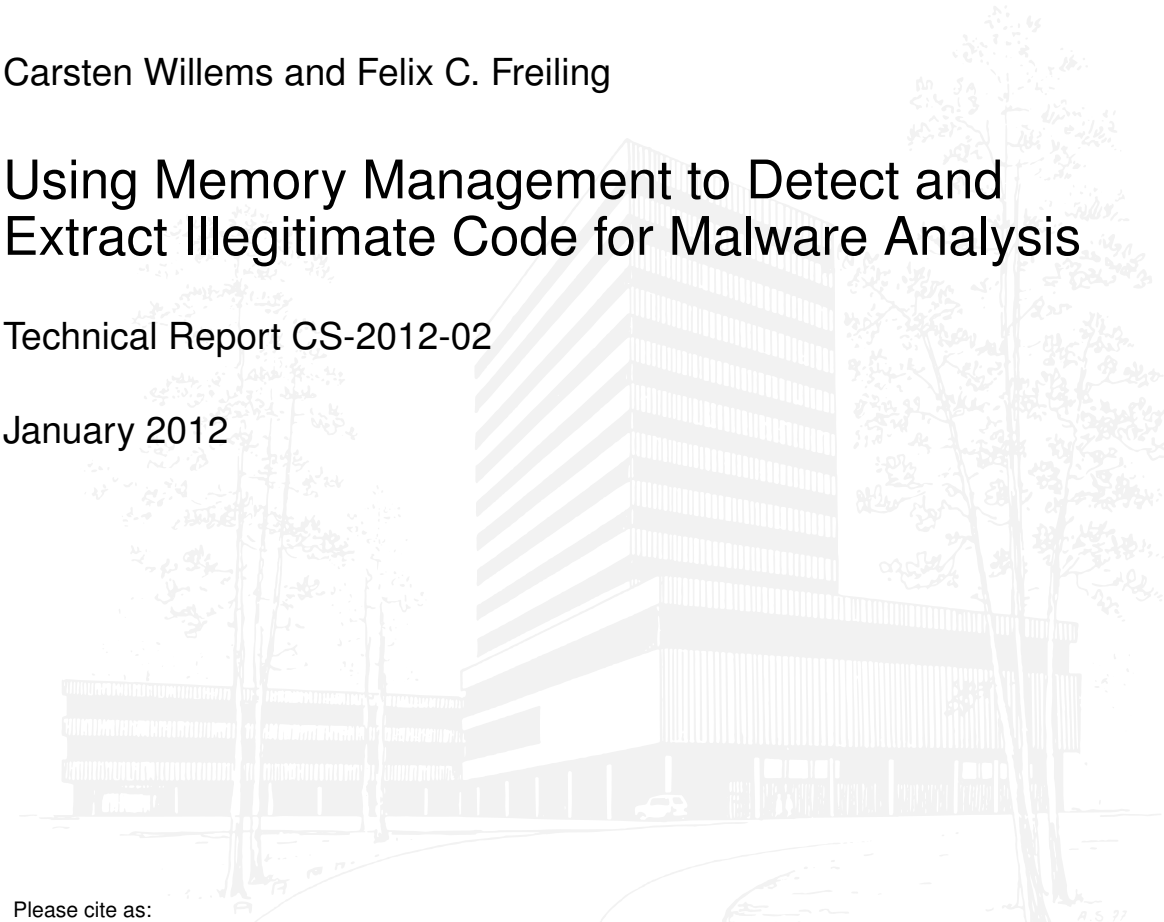

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Using Memory Management to Detect and Extract Illegitimate Code for Malware Analysis

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***Abstract*—Exploits that successfully attack computers are mostly based on some form of shellcode, i.e., illegitimate code that is injected by the attacker to take control of the system. Detecting and extracting such code is the first step to detailed analysis of malware containing illegitimate code. The amount and sophistication of modern malware calls for automated mechanisms that perform such detection and extraction. In this paper we present a novel generic and fully automatic approach to detect the execution of illegitimate code and extract such code upon detection. The basic idea is to flag critical memory pages as non-executable and use a modified page fault handler to dump corresponding memory pages. We present an implementation of the approach for the Windows platform called *CWXDetector*. Evaluations using a large corpus of malicious PDF documents show that our system produces no false positives and has a similarly low false negative rate.**

I. Introduction

A. Motivation

No matter what particular exploitation method or target is used, the ultimate aim of an attacker is to perform *malicious computation* on the target system, i.e., to execute machine instructions whose type and order are under the complete control of the attacker. Usually, malicious computation is caused by *illegitimate code*, i.e., code that was not intended to be executed, neither by the developer of the exploited process nor by the end-user of the system. Such code is usually injected into the target system using external data like network traffic or application files.

This document is an extensive revision of a previous technical report [1] and was extended in several ways. For example, we describe more detection results and have revised the complete extraction result section.

As a countermeasure to this increasing threat, operating systems try to *prevent* the execution of illegitimate code using techniques like *Data Execution Prevention* (DEP) [2] and *address space layout randomization* (ASLR) [3]. However, prevention alone does not generally help in the analysis of illegitimate code. Therefore, it is necessary to develop mechanisms that *detect* and *extract* illegitimate code from malicious data. A consecutive analysis of the extracted data then assists in developing new protection techniques and creating signatures for zero-day malware until patches are available.

In this work we present CWXDetector, a new tool for the analysis of malware for the Windows operating system. It performs a dynamic analysis for detecting and extracting illegitimate code by instrumenting the memory management features of the operating system itself. Roughly speaking, the idea of the approach is to mark critical memory pages as non-executable. This ensures that upon execution of code in these regions the page fault handler of the operating system is called. This usually suffices to *detect* illegitimate code. However, to *extract* illegitimate code, we modify the page fault handler so that the memory page that caused the page fault gets dumped for later analysis.

Note that *CWXDetector* is not meant to *protect* a system, but to monitor and analyze the execution of illegitimate code. Our system even disables some security measures like DEP for that. Nevertheless, there are some similarities in other preventive and analysis techniques that we now discuss.

B. Related Work

1) Preventive Measures: A large body of related work mainly aims at the *prevention* of malicious code execution, mostly following the *reference monitor* ap-

proach. Many such methods are directly integrated into contemporary compilers and operating system [4]. However, often newly introduced protection techniques are incompatible to existing old applications and, therefore, can be disabled by the applications themselves or are deactivated per default. *Microsoft's EMET tool*[5] tries to overcome this problem by allowing a process-specific configuration of these protection methods and their enforcement. Other methods restrict memory write operations or control transfers. Kiriansky, Bruening and Amarasinghe [6] as well as Abadi et al.[7] use code rewriting techniques to implement the monitoring. The main difference to our work, is that those solutions terminate the monitored process in the event of a security violation, and are not able to produce any further analysis data. Furthermore, they all lack of capability to handle self-modifying or dynamically created code and they are not able to handle specific types of exploits (like SEH-related ones) under certain circumstances (e.g., if libraries are involved that have the *SafeSEH* feature disabled). Finally, all described measures aim solely at the prevention of malware exceution, but offer no assistance in their further analysis.

2) Detection of Illegitimate Code: The detection of illegitimate code is an extremely difficult problem today. Early attempts relied on static signatures [8], but those had to be improved due to the heavy use of polymorphism, encryption and other obfuscation methods. More enhanced methods try to detect certain invariant parts of the shellcode, e.g., Akritidis et al. [9] search for the typical "sled component" in such code. Others have used heuristics in combination with *dynamic* analysis methods to detect illegitimate code. For example, machine learning methods have been used to deal with the variable parts, e.g., Payer, Teufl and Lamberger utilize a neural network [10] in combination with *execution chain evaluation*. Polychronakis, Anagnostakis and Markatos [11] use emulation to detect an ongoing decryption process which is typical for polymorphic shellcode. Also Baecher and Koetter [12] use an emulated environment to identify and isolate shellcode with the help of *GetPC heuristics*. Overall, and in contrast to *CWXDetector*, these signature- or heuristics-based approaches are not fully generic and have to be extended when new anti-detection measures of malicious code come up.

It has been observed before that memory management can be used to detect illegitimate code execution. For example, the *PaX project* [13] proposes several different measures to implement non-executable memory — even on architectures with no hardware support for that. Also hardware-DEP utilizes the *no-execute* (NX) flag in the Windows page table to make particular memory pages non-executable. However, and in contrast to our approach, these techniques do not allow to *extract* illegitimate code since they totally block the execution of illegitimate code.

3) Extraction of Illegitimate Code: There exist several solutions aiming at the extraction of illegitimate code, especially automated unpacking of malware. These mechanisms usually interact deeply with the memory management of the underlying operating system. In all cases those solutions try to detect the execution of memory regions which have been written to beforehand. *OllyBone* [14] implements this by instrumenting the *translation lookaside buffer*. Since *OllyBone* is a debugger-plugin, it imposes all the disadvantages of debugger-driven malware analysis, e.g., its detectability. Another disadvantage that contrasts it to our approach is that it is a semi-automated process, in which execution is stopped at the first occurrence of malicious instructions and the human analyst has to continue with further extraction steps. Finally, it is not able to deal with dynamically allocated memory regions (since it focuses on Windows PE sections).

OmniUnpack [15] uses an approach similar to the *PAGEEXEC* method proposed by PaX, i.e., the *User/Supervisor* page table flag is used to automatically break on the execution of certain monitored pages. In order to decide whether executed and previously written memory should be considered as malicious, an external detector is used to scan unpacked memory for the existence of malicious code. That detector, again, has to use signatures or heuristics that generate a lot of false positives, especially if a JIT-compiler is involved. Finally, executed memory is only considered if a critical system call is executed afterwards. Our approach uses a more effective heuristic based on the concept of *trusted callers* that results in much better detection results.

Renovo [16] runs the sample in an emulated environment (TEMU [17]) and maintains a shadow memory to track written memory regions. Since this cannot be done on a native system, the system cannot be realized *without* system-emulation. Again, like with debuggers, this enables the monitored malware to easily detect the synthetic environment.

C. Contributions

CWXDetector is a new dynamic approach for detecting and extracting illegitimate code. The power of the approach stems from its simplicity in using the page

fault handler of the operating system itself. Therefore, the challenge is to evaluate its effectiveness in practice. This means to evaluate it for the Windows platform of operating systems, since this platform is still the major target of illegitimate code today. Unfortunately, Windows is not an open source operating system and without proper documentation it is a tremendously difficult task to integrate custom functionality into the kernel. Therefore, we had to perform a lot of substantial reverse engineering regarding the internal memory management mechanisms of the Windows kernel [4]. Based on these insights, we modified the kernel of a x86 Windows XP operating system by establishing a custom *page fault handler* and intercepting some essential memory related *system functions*.

We evaluated our approach by considering the task of detecting and extracting illegitimate code in/from a particulary relevant class of application files, namely those in Adobe's portable document format (PDF) [18]. Our approach proves to be very effective. We analyzed a set of 7,278 malicious PDF documents using a set of vulnerable versions of Adobe Reader and achieved a detection rate of 93.2%. This can be regarded as a lower bound for our method since many of the investigated PDF files appeared to be broken although they were flagged as malicious by Antivirus products. We also analyzed the same amount of benign PDF documents, resulting in a (false positive) detection rate of 0%. Furthemore, our detection results compare favorably to those of application specific detection tools like *Wepawet* [19], *PDF Examiner* [20] and *ADSandbox* [21], but outperforms them by being generic and -to some extent- also being capable of detecting zero-day exploits. To further demonstrate the universality of our approach we also used it to detect shellcode execution in *Flash Player*, *RealVNC client* and *VideoLan Client*.

To summarize, the contributions of this paper are twofold:

- We present a generic and fully automatic approach to detect the execution of illegitimate code and extract such code upon detection.
- We successfully evaluate our approach using malicious PDF documents as example and show that we can improve state-of-the-art tools.

To some extent our approach is similar to DEP [2], which totally disables the execution of certain memory regions. This is accomplished by employing the NX flags of the related page table entries in a similar way like we do it. Nevertheless, there are big differences between DEP and our system: first we do not completely prohibit the execution of illegitimate code, but we intentionally allow it in order to get detailed analysis results. On the attempt to execute non-executable memory, we dump the memory page that contains the code, and then continue execution in order to obtain more information. Secondly, we do not only take the type of memory into account when deciding which should be monitored respectively executed, but we also check the initiator of memory related modifications and allocations. As an effect we are able to correctly handle cases in which malicious executable modules are mapped into memory, or when DEP-conquering shellcode allocates regular executable memory.

To some degree our system also constitutes a *reference monitor*, that is restricted to monitor accesses to executable memory. In contrast to the *inline* solutions proposed in the past [6], [7], we do not modify the monitored application itself, but the underlying operating system and incorporate hardware features to perform the monitoring. This has several positive effects: it is much easier to extract the executed memory, since we are already residing within the page fault handler. Furthermore, we do not have any problems with dynamically created or self modifying code. Finally, we do not have to manually track any control transitions, i.e., some of the related work in this topic is unable to detect control flow transitions that occur due to *structured exception handling* and not due to a regular branch instruction.

D. Limitations

Our method is solely based on dynamic analysis of the examined malware samples. Therefore, it suffers from all the drawbacks and limitations of dynamic analysis in general. Since during each code execution only one particular control path is taken, the gained results always may be incomplete. If a required environment condition is not met and, therefore, a certain malicious functionality is not triggered during execution, dynamic analysis is unable to reveal any information about it. Accordingly, our system is incapable to detect malicious code which is embedded in arbitrary data in general, but only detects such code when it gets executed.

Furthermore, the existence of malicious computation does not always imply the existence of illegitimate code. Therefore — and similar to DEP — our approach has problems with novel exploitation techniques like *return oriented programming* (ROP) [22] or *JIT-spraying* [23], [24]. However, advanced attacks usually consist of multi-

ple stages of which only the first uses ROP/JIT-spraying to set up a later stage comprising regular illegitimate code which then can be detected and extracted using our method.

Obviously, our system is not meant to protect end consumer hosts, but its sole purpose is to support malware analysis on dedicated analysis systems.

E. Structure of this Paper

This paper is organized in the following way: Section II defines our attacker model and some necessary terms. In Section III we describe our approach in general, whereas Section IV illustrates an implementation for the Windows XP operating system. In Section V we explain how our system can be applied to the analysis of malicious PDF documents. We evaluate our approach and present the *detection* results in Section VI and the *extraction* results in Section VII. Section VIII concludes this paper and gives topics for future work.

II. Model and Definitions

In this section we specify our attacker model, define the term *illegitimate code* and further concretize our two aims: the detection and extraction of executed illegitimate code.

A. Attacker Model

In this work we assume a remote attacker that provides some malicious piece of data in order to exploit a vulnerability in some handling application resulting in the execution of shellcode. This data may have arbitrary form, e.g., a specially crafted PDF document or a malicious input packet to some network application.

As mentioned above, we are aware of the threats posed by ROP [22] or JIT-spraying [23], [24] techniques, but nevertheless assume that an attack does not *fully* consist of such code. To the best of our knowledge, we are not aware of any documented instance of such a single staged *full*-ROP/JIT-sprayed attack in the wild.

B. Illegitimate Code

Our approach enforces the partitioning of executable memory into regions that contain legitimate code and those that may contain illegitimate one. Additionally, it monitors and restricts the execution of instructions that are located in illegitimate code regions. Intuitively all code that belongs to the operating system or to a known application is legitimate. For realizing this distinction, we first partition the files of a system into a set of trusted files and a set of untrusted ones. We assume that such a distinction is given, e.g., by defining all files in a freshly installed system as trusted. For dealing with dynamically created code, we identify those code portions contained in trusted files that should be allowed to allocate executable memory. Accordingly, we partition each trusted file into trusted memory modification functions and untrusted ones. Again we assume such a distinction is given, e.g., by defining all required code emitting memory functions of the operating system as trusted and all others as untrusted. Then, *legitimate code* (LC) is code which is either contained in a trusted (system or application) file or it is code that was dynamically created by any of the trusted functions from one of those files.

We now define *illegitimate code* (ILC) as code that is not legitimate. Intuitively, ILC is code which would not be executed if the operating system and the installed applications would function properly. In practice it is code that is either injected by or constructed on behalf of an attacker by some malicious piece of software or data. Therefore, ILC is similar to *shellcode* in its current understanding.

C. Problem Statement

The aim of the system described in this work is to perform two tasks automatically:

1) We wish to *detect* the execution of illegitimate code, and
2) to *extract* it, i.e., dump all relevant memory pages to disk, for a later in-depth analysis.

III. Approach: Instrumenting the Page Fault Handler

In the following we describe our approach and how it can be applied to the dynamic analysis of malware.

A. Enforcing an Invariant

Based on our attacker model, no matter what kind of exploit is used in an attack, the resulting effect is always the execution of illegitimate code like we have defined above. When a vulnerability is exploited, the control flow is redirected to one of the following locations:

1) ILC on the stack *(buffer overflow)*,
2) ILC in the heap *(heap-spraying)*, or
3) ILC in a static data area *(exploiting a static data buffer)*.

Throughout our approach, we establish and maintain the following invariant condition:

All ILC resides in *non-executable* memory.

As an effect to this invariant, all execution attempts of ILC will result in the invocation of the *page fault*

handler of the operating system. By implementing our own custom page fault handler, we are able to react on such attempts appropriately.

B. Trusted Files and Functions

To establish the invariant, we need to identify the set of trusted files and functions. For simplicity we trust all files which have been already existing when we start our analysis, and distrust all files which were created or modified during later system operation. To achieve this, we need to keep track of file manipulation operations. Therefore it is necessary to intercept ("hook") the system service that is used to create files or open them with write-access.

For each trusted file we further define a set of *trusted memory modification functions*, which contains all the functions that are allowed to dynamically create executable memory or modify the protection settings of already existing memory to being executable. The set of all such functions from all trusted files is called *trusted callers*.

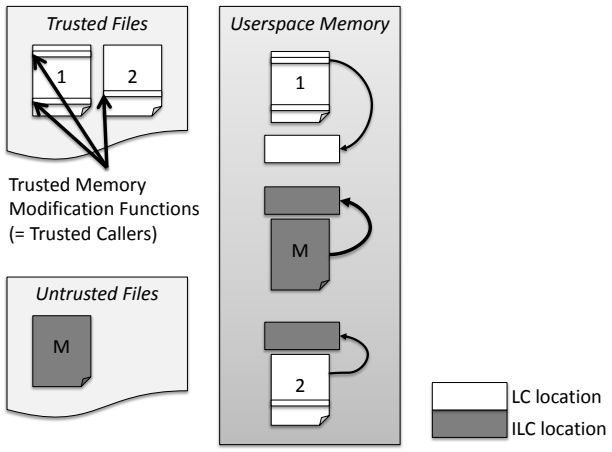

Fig. 1: Trusted Memory Modification Functions

Figure 1 illustrates our understanding of trust, showing an example with two trusted and one untrusted file. While trusted file 1 contains two trusted memory modification functions, trusted file 2 only has one. Obviously, the untrusted file can not contain any trusted function at all. The simplified version of the userspace memory shows that all three files have been mapped into the virtual address space. The memory related to the trusted files only contains trusted code, hence constitutes LC memory, whereas that memory of the untrusted file may contain illegitimate code. Furthermore, each mapped module has allocated one dynamic memory area, pointed to by the corresponding arrow. That area belonging to file 1 was created by a trusted caller and, hence, may contain legitimate executable code. But the memory created by the untrusted caller from file 2 as well as the region created by the untrusted file may contain ILC and, therefore, are marked as ILC locations.

C. Memory Protection Modifications

Obviously it is necessary to intercept attempts to modify the memory protection, because this can result in executable memory. This is realized by hooking critical system calls. Inside these hook functions we enforce the following points to maintain our invariant:

- only trusted callers can allocate executable memory,
- only trusted callers can modify existing memory to being executable, and
- only trusted files can be mapped into executable memory.

All attempts that violate these rules are intercepted and the resulting memory regions becomes *non executable*.

In summary, only trusted files can be loaded into executable memory and only trusted callers can create executable memory. There is one exception: even if a *trusted caller* tries to modify the memory protection, intervention may be necessary under special circumstances: if the related target memory belongs to a mapped trusted file and should become writable, the executable right has to be removed. This enforces the $W \oplus X$ property [2]. In general, all legal linkers should produce files which fulfill this requirement anyway. Nevertheless, we enforce it on our own to also handle files securely which violate it by intent or accident.

The realization of making memory non-executable strongly depends on the underlying system architecture and also on the operating system. Many contemporary CPUs offer an *execute disable* (NX) protection flag on a page level. Nevertheless, this feature can be only used for valid page table entries (PTEs) and, therefore, in most cases some additional OS memory objects may have to be modified as well.

D. Custom Page Fault Handler

The heart of our detection method is the *custom page fault handler*, which reacts on the attempt to execute memory regions which we have marked non-executable beforehand. As described above, all necessary prerequisites are already done when new memory is allocated or the protection of already existing one is tried to be modified. Accordingly, the custom page fault handler only has to *wait* until a protection-related page

fault is triggered. In that event, we have to check if the occurred page fault is really related to our system modifications. If so, we have detected the execution of illegitimate code and, as a result, we dump the related memory page to hard disk. After that, the related memory region is modified by us to being executable, such that the current and all further execution attempts for this page will become successful. This is done because we do not want to stop our analysis process once the first illegitimate instruction is found. Finally, we resume the current process and wait for the next fault.

E. Multi Version Dumping

In order to avoid detection, shellcode very often is built by multiple stages that are organized like a russian stacking doll (*matrushka*). Each stage is only a small stub that deobfuscates or decrypts the next stage and then transfers control to it. Since the effective malicious instructions are mostly contained in the final stage, it is desirable to unpack it automatically. Therefore, we apply a feature called *multi version dumping* (MVD), in which different versions of each executed page may be created. To that end, an internal copy of each dumped memory page content is stored and if the content is modified later on, another dump file is created. By comparing two consecutively created dumps, we can easily isolate those parts that have been modified and infer the decrypted shellcode instantly.

Notice, that not every shellcode is multi-staged. Therefore, sometimes only one dump file is created for a detected ILC containing memory page, and sometimes two or more. If multiple versions are created, we normally are only interested in the final one, since we assume that it contains the fully decrypted code.

IV. Windows-based Implementation

In the following section we illustrate *CWXDetector*, which is the concrete implementation of our approach for the x86 version of Windows XP. We utilize the PAE kernel version of Windows, since only this one supports the NX page table flag that we utilize to realize non executable memory. Although that kernel version was originally intended to support physical memory that is larger than 4 GB, it is nowadays used on all installations of the 32 bit Windows XP version that have DEP enabled.

In summary, to realize our approach we need to

- define trusted files and trusted callers,
- implement hook functions for memory allocations and protection modifications,
- implement a custom page fault handler to detect and react on ILC execution, and
- additionally modify essential system functions to support our approach.

Since Windows is not an open source operating system, a lot of reverse engineering had to be performed previously, especially on the underlying memory objects like VADs and PPTEs. The resulting findings are explained in detail in an additional technical report [4]. Though the implementation of *CWXDetector* seems to be straight-forward, the unavailability of the Windows source code poses enormous difficulties when intercepting kernel system calls, customizing the page fault handler and patching OS-controlled memory management resources.

A. Memory Function Hooks

In order to ensure that only legitimate code resides in executable memory, we redirect the calls of **NtAllocateVirtualMemory**, **NtProtectVirtualMemory** and **NtMapViewOfSection** to custom hook functions in order to fulfill the invariant from Section III-A. On a lower level we realize non-executable memory by modifying the related memory structures, i.e., the *execute disable* (NX) flag of the related page table entry as well as the *VAD entry* and the *prototype PTEs* of the corresponding memory regions. Section A in the appendix presents more implementation details of the hook functions.

B. Checking the Caller

In order to restrict the memory creation and protection modification attempts of executable memory, we need to check the particular initiator of such operations against the set of trusted callers. For that we have to walk the usermode call stack to a certain depth and inspect the saved return addresses. Since our hooks functions reside in the kernel, we therefore need to gather information about the current usermode context, from which the kernel call has been performed. This kind of information is stored within the *trap frame*, which can be accessed from kernel mode via the **KTHREAD** structure that exists for each thread. Section A in the appendix gives further information on how the caller function chain can be obtained from this structure.

C. Custom Page Fault Handler

We hook the Windows system function **MmAccessFault** to implement our custom page fault handler. The code of this hook function is rather short, since all necessary prerequisites are already done by the other

hook functions. First, we call the original page fault handler to actually resolve the fault, e.g., validate the related PTE. Then we check if the fault was caused by an *execute* operation and if the faulting address resides in user space. If so, we further verify if the target address is valid, which can be determined easily by inspecting the values of the related PDE and PTE. If all these conditions are met, a dump file of the related memory page is created and the protection settings of the associated PTE are modified to executable. A further modification of the PPTE and VAD entry is not necessary here, since protection settings stored with those objects are never used again, once a PTE was created from them.

D. Additional System Modifications

For distrusting all files which were created or modified during our analysis, we hook the system service **NtCreateFile**, which has to be called to create new and open existing files. Furthermore, we hook **NtCreateProcess** to monitor and restrict the creation of new processes.

V. Application to the Analysis of PDF Documents

Our approach is completely generic and can be used in different scenarios. In order to further illustrate it and evaluate its effectiveness we apply our tool *CWXDetector* to the field of dynamic analysis of malicious PDF documents. Malicious documents as attacking vector have become very popular in the past few years, and especially the *portable document format* (PDF) is a commonly used medium for malicious content.

One reason for that is the extensive feature list of PDF documents. It offers the two programming languages *Javascript* and *Actionscript* and the possibility to embed many different object types like images, sounds and even executables. Another reason for the increasing number of exploitation attempts is the complexity, and hence error-proneness, of the PDF format itself and its viewer applications. For example, the latest PDF reference [25] from 2008 contains 756 pages and *Adobe* already has published several extensions to it meanwhile.

A. Dynamic PDF Analysis

During dynamic malware analysis in general the object under investigation is not disassembled, but viewed as a *blackbox* and actually used in its intended way: an executable is run, a document is opened in its associated viewer application and so forth. This has several negative impacts: first of all the testing environment may get infected, since the malicious code actually is executed. Secondly, it may happen that though real malware is analyzed, no malicious operation may be observed at all. There are always some necessary requirements to the environment, under which particular exploits may only work, e.g., a vulnerability may be fixed in a newer version of the affected application or an exploit aims only at a particular language version of a software. Accordingly, dynamic analysis in general is *incomplete* and we try to address this disadvantage by testing each PDF sample in different viewer applications and then combine all the findings. Though not usual, a malicious functionality may only be triggered on a certain user action or input. In order to correctly analyze those files as well, user-simulation could be employed[26] as an extension to the existing functionality.

In order to analyze PDF documents with our system, we have set up multiple virtual machines with 32 bit Windows XP SP2 and installed a different PDF viewer application on each of them. In particular we have used the *Adobe Acrobat Reader* versions 6.0.0, 7.0.0, 7.0.7, 8.1.1, 8.1.2, 8.1.6, 9.0.0, 9.2.0 and 9.3.0. For comparison we also have set up one machine with *Foxit Reader* version 3.0.0 for which also some vulnerabilities are known. This particular application and version set have been chosen to cover the most of the known vulnerabilities for PDF documents, but it should be mentioned, that it may not be optimal nor have full coverage for all known existing exploits.

Each PDF sample is analyzed in all of those machines in parallel. During the analysis we performed the following steps on each machine separately:

- We installed our customized page fault handler and our system hooks.
- We started the particular viewer application.
- We disabled DEP for the viewer application, since otherwise the execution attempt of non-executable code would crash the process and we would not have any possibility to intercept it in our custom page fault handler.
- We opened the PDF document in the viewer application.
- If new memory was allocated or existing memory was modified during execution, we enforced the invariant from Section III-A.
- If the execution of illegitimate code was detected, we dumped the associated memory page to a file, created a describing log entry, and modified the related PTE to being executable. We then checked the dumped memory page for typical patterns of illegal code (appendix A). In case these could be

found we marked this case as "*PATTERN*" in the log file.
- If a new process was created by the PDF viewer, we created an entry marked "*PROCESS*" in the log file. We prevented the spawning of additional processes since we are only interested in analyzing exploits in the PDF viewer application itself.
- If a dialog window was shown by the PDF viewer, we created an entry marked "*DIALOG*" in the log file and additionally logged the contents of the window. We then simulated a user input to close the window and continue viewing the PDF document.

For scalability reasons the analysis process was stopped after a specific timeout, which was set to two minutes in our experiments. As mostly all known malicious PDFs trigger their malicious operations instantly when viewing the first page of the document, it is safe to assume that we will have seen mostly all malicious shellcodes after this amount of time. In many cases that timeout was not reached, because the PDF viewer application terminated prematurely. In that case we marked this execution as "*CRASH*" in the log file. Finally, and if none of the aforementioned special cases above have been occurred (*PATTERN, DIALOG, PROCESS, CRASH*), the case was labeled as *NOTHING*.

After the analysis we extracted the dump and log files from the machine and then reverted it back to a clean state. What we finally got as result is a set of dump files that contain the memory contents of each page from which illegitimate code was executed. Furthermore, we got a logfile that contains information about:

- All attempts to allocate executable memory which are not invoked by a trusted caller,
- all attempts to modify existing memory to being executable, which are not invoked by a trusted caller,
- all attempts to execute memory that contains illegitimate code,
- all created files (needed during analysis to maintain the list of untrusted files),
- all created processes (needed for evaluation and debugging purposes), and
- all shown user dialog windows.

Overall, every PDF file ended up with a combination of two labels (d, c): the first label d determined whether illegal code was detected or not, and the second label c was either *PATTERN*, *CRASH*, *PROCESS*, *DIALOG*, *NOTHING* as defined above. Since different PDF viewers can react differently to a single PDF file, we needed to aggregate all the different results into one overall value. We defined a lexicographic total order on the tuples as follows: $(d, c) > (d', c')$ if and only if either d had detected illegal code and d' not, or (if $d = d'$) $c > c'$ according to the following ordering:

$$\textit{PATTERN} > \textit{CRASH} > \textit{PROCESS} > \textit{DIALOG} > \textit{NOTHING}$$

We used the highest occurring value as combined overall value.

In Section VI and VII we describe our findings and the results of our experiments in detail. Nevertheless, in general we are interested in the fact if a viewed PDF document triggers the execution of ILC or not. If we are able to detect such an attempt, we call our result a *true positive*. If we fail to detect it, we call it a *false negative*. If on the other hand, a benign PDF document is analyzed and in reality no ILC is executed at all, but our system erroneously reports ILC execution, we call this a *false positive*. Finally, a *true negative* stands for such a case, in which our system correctly does not report ILC execution.

B. Determining Trusted Files and Callers

As explained in Section II-B we have to define the set of *trusted files* and the set of *trusted memory modification functions* (trusted callers) for each of them. The set of trusted files is easy to determine. Since we perform each analysis on a clean and uninfected system, we simply define all existing files as trusted ones and all files that are created or modified during the analysis as untrusted ones.

For specifying the trusted callers, we have to identify all the functions from all trusted files that are used to produce executable memory, e.g., we have to search for all calls of memory-related APIs and inspect the used parameters that specify the protection settings of the resulting memory. This may be done fully-automated, but we have used a semi-automated process, in which we have started with a white-list that only contained the loader-related function from ntdll.dll. Then we have loaded benign PDF documents into the different PDF viewer applications and if we have encountered a *false positive*, we have manually inspected the disassembly of the related function call and extended the white list appropriately. This process is fail-safe, since we may only get *false positives* if we have forgotten particular trusted callers, but will never create *false negatives* if we set up our trusted caller list correctly.

In the end we came up with only three files that had to be taken into account: *ntdll.dll, AcroRd32.exe*

and *authplay.dll*. All of those contain functions that allocate executable memory or modify existing one to being executable. *ntdll.dll* contains the Native API and especially the Windows loader functionality, which of course, has to be able to create executable memory. For the particular Windows version we are using, this is done from two different locations within **LdrpSnapIAT** and **LdrpSetProtection**. *Acrobat Reader* from version 9 on upwards contains a JIT-compiler that also allocates executable memory. We have checked the affected library *authplay.dll* and verified that the **VirtualProtect** API is called from two different places. Since only one of those calls is used with an *executable* protection value, we only have to put this one on to the list of trusted callers. Finally, we have observed *Acrobat Reader* in version 7.xx to allocate executable memory from an MFC function **CLangBarItemMgr::CreateInstance**. Hence, we also take care of these calls.

VI. Detection Evaluation

We have evaluated the detection quality of our system by means of two different experiments. First, we have performed a comprehensive analysis of PDF documents. For that purpose we have created two sets of PDF documents of size 7,278 each (a *benign* set and a *malicious* set) and used *CWXDetector* to analyze these files. We have developed heuristics to measure the correctness and completeness of our findings. We further have compared our generic system against several other analyzers, that use application-specific knowledge to analyze PDF documents. In a second experiment we briefly illustrate the universality of our approach by applying our tool on malicious *Flash* documents and network packets.

A. Benign PDF Sampleset

In order to test the *false positive* rate of our approach, we obtained a set of known benign documents, which contain as much different PDF features as possible. Accordingly, analyzing them enables us to monitor various different behaviors, in form of code coverage of the PDF viewing application. We constructed this set using the following method:

- We retrieved URLs of the TOP 5000 Internet sites from www.alexa.com.
- We queried Google for the first 10 PDF documents on each site and downloaded them.
- Using the tool *pdfid* [27], we selected all documents which contained *JavaScript*, *OpenActions* or some other extended PDF features.
- We uniformly picked random samples from the other downloaded files until the total set of files consisted of 7,278 samples (the same size of the malicious sample set, see below).

The final set has the following characteristic: altogether it contains 7,278 samples, 600 of which contain *Javascript*, 782 contain *AcroForms*, 1,573 samples have an *OpenAction* and 751 some *AdditionalAction*.

All samples have been verified by Virus Total [28] and in 3 cases one or more AV scanner delivered a positive result. We checked those samples by hand and did not find any malicious content within them. Therefore, most probably these detections are AV false positives.

We ran our system on the benign sample set. As a result, we did not detect *any* single ILC execution, hence we have a *false positive* rate of 0%.

To speed up the analysis, we only used the three "most vulnerable" PDF viewer applications for the benign sample set (namely *Adobe Acrobat Reader 7.0.7, 8.1.1* and *9.0.0*). Since the achieved false positive rate of our experiments was so low, we can assume that it will not increase dramatically by using more different viewers.

B. Malicious PDF Sampleset

We obtained a set of 7,278 known malicious PDF documents from a well-known AV vendor. The set consisted of all their valid incoming PDF samples from January 2011. These samples originated from different sources as shown in Table I. We checked all samples with the publicly available service Virus Total [28] which confirmed that all of them were indeed malicious.

TABLE I: AV Sample Sources

Source	Fraction
AV Sample Sharing	70.0%
Found in the Wild	24.0%
Multiscanner projects	4.8%
Intercepted botnet traffic	1.2%

We ran our tool on the malicious sample set and were able to detect and extract executed ILC in 93.2% of all cases. The detailed analysis results are shown in Table II and are explained in the following section.

C. Discussion

Given the benign and malicious data sets as stated above we end up with a false positive rate of 0% and a false negative rate of 6.8%. However, we have seen a lot of samples which were broken and, though containing malicious content, were not able to produce malicious functionality when loaded into a PDF viewer.

TABLE II: Overall Detection on Malicious Samples

	ILC detected		**no** ILC detected	
	Samples	Fraction	Samples	Fraction
PATTERN	6,658	91.5%	—	—
CRASH	20	0.3%	15	0.2%
PROCESS	83	1.1%	33	0.4%
DIALOG	0	0.0%	295	4.1%
NOTHING	20	0.3%	154	2.1%
Total	6,781	93.2%	497	6.8%

Furthermore, some samples only triggered their exploit when using a particular PDF application that was *not* contained in our application set. Finally, there exist some samples that perform malicious behaviour that is not based on shellcode, but instead uses built-in features of the PDF viewer application. For instance some samples redirect to malicious websites or exploit software bugs in third-party applications, which can be started directly from within a PDF document. To fortify our results and argue why we assume an effective false positive rate that is much lower than the measured one, we analyzed the documents from the malicious data set in more detail.

1) Results without ILC Execution Detection: We investigated the 497 PDF documents for which *no* ILC execution was detected. If we would be able to prove that none of them have executed any ILC within our used environments, our detection rate would increase to 100%. However, since we are not able to manually analyze about 500 samples, we developed heuristics to find at least hints that lead to the assumption that these samples really failed to perform malicious computation.

We first checked those 15 files that crashed the PDF viewer. We verified if the crashing operation is contained in any of the regular modules that belong to the PDF viewer. In that case most probably some exploit went wrong or the PDF consisted of an invalid structure, which lead to an erroneous termination of the parsing application. Of course, we cannot be completely sure that no illegitimate code has been executed beforehand, but since we have seen many corrupt and broken PDF documents, it is very probable that we have not missed anything but the viewer just has crashed before any illegitimate code could be executed. After manually checking all 15 samples we found that indeed all of them performed invalid memory accesses. So overall those samples are malicious too but simply fail to execute their shellcode due to incompatibilities with the underlying PDF viewer or other aspects of the environment.

We then examined those 33 samples that created a new process. At first view one could suppose that starting a new process is a sure sign for a malicious activity. However, we discovered that in all cases regular built-in features of the PDF viewer were used for that and no illegitimate code was involved. The started applications are *Internet Explorer (iexplore.exe), Outlook Express (msimn.exe)* and the *Command Shell (cmd.exe)*. In most cases the parameters used when starting the Internet Explorer or Outlook Express are specially crafted to enforce a parsing error and arbitrary code execution. Section A in the appendix gives examples of those used parameters.

After that we investigated the 295 cases that where classified as "*DIALOG*". Most of the dialogs contained error messages of the parsing engine, which state that the PDF structure itself or some embedded JavaScript-code was invalid. We assume that either the corresponding PDF documents were corrupted or that we simply have not used the expected environment to trigger the malicious functionality. In addition to this, there are some PDF exploits that solely are based on social engineering, in which the user is tricked to respond in a particular way to the shown dialog. For example the warning message for starting a new process is obfuscated in a way such that the user will not notice that a new process will actually be spawning when he clicks the *OK* button [29], [30]. In Section A of the appendix we present some examples of the encountered dialog messages. Overall, it is unclear whether these files are indeed malicious. However, it is also highly probable that none of them executed any form of ILC during execution.

Finally, 154 samples did not perform any suspicious activity at all. Obviously, this does not mean necessarily that the samples are harmless. It just means that under the given environment they behave benign. One reason for not triggering detection could be that we have not used the correct PDF viewer environment which is necessary to trigger the exploit. We manually checked a representative random set of 30 samples of this class and we found that they do not contain any working exploit at all. A reason for the AV scanners to mark them as malicious may be that they contain pattern from their virus signature databases. This may be either a pure coincidence, or it may be the result of a failed attempt to create a working malicious PDF document.

Overall, given the above findings, it is safe to assume that in all 497 cases no ILC was executed. So while our method failed to flag these samples as malicious, it succeeded in detecting the execution of ILC: since no ILC was executed no detection was triggered. In this sense all negatives are true negatives, and so after careful

consideration one could also claim a false negative rate of 0% for our approach and the examined sample set.

2) Results with ILC Execution Detection: For completeness, we also discuss the cases where our method detected ILC execution. In order to show that these cases are correct, we have to ensure that all dumped memory really consists of illegitimate code and that no prior ILC execution has been missed. Again, confirming this for each individual case is impossible due to time restrictions and, therefore, again we used heuristics to get trustful hints for the correctness. In the 6,658 cases that are flagged *PATTERN* we confirmed the presence of known shell code patterns in the dumped memory pages. Therefore, we can be sure that in fact ILC was executed.

We checked those 20 samples that crashed the PDF viewer after the ILC detection. This is also a clear sign for (a partly failed) malicious behavior. In such cases the exploit did not work well, either because it was badly programmed or because it did not discover the environment which was needed to work correctly. Even if the samples do not succeed to perform any reasonable malicious operation, we know that the observed code execution really is related to ILC and, accordingly, is no false positive. All of the 20 samples crashed due to an access violation when performing reading, writing or executing memory operations on invalid regions.

Next we investigated those 83 PDF documents that spawned new processes after the ILC execution. This is clear sign of beforehand executed ILC since the test system was set up in a way that prevented new processes from being spawned "legally" as an effect of just viewing a PDF document. One exception to this are the applications mentioned in section VI-C1 that are an effect of performing built-in features. We have verified that none of the spawned processes belong to those exceptions, but all fall into one of the following three categories: it is either tried to perform malicious operations from within a second extracted or downloaded malware, to open a benign PDF document in order to hide the maliciousness of the initial document or to gather essential information about the exploited system. Accordingly, we can be sure that all of these samples really have executed shellcode. Section A in the appendix contains examples of the processes from all three categories.

Finally there are 20 remaining samples with ILC execution, for which all of our previously described heuristics fail. Hence, we are not able to tell anything automatically about their maliciousness and, therefore, we have checked them manually. All of them really execute illegitimate code, from which some is simply not working correctly and other does not even consist of valid machine instructions at all. We can only guess the reasons for that: most probably some of these samples just were written badly or got corrupted due to some transmission error. Others may find some unexpected environment and, accordingly, do not function well. Anyway, we have manually assured ourselves that in all cases ILC was executed, no matter if the resulting operations were valid or not.

3) Detection Summary: Though we are not able to manually verify all the samples we have analyzed with our system, the results shown in the previous subsections lead to the conclusion that our approach works well. If we aggregate all our findings with illegitimate code execution, we get a minimum detection rate of 93.2% for our particular set. If we furthermore assume that there is a serious fraction of samples that do not contain working shellcode for any of our used environments, we get a much higher detection rate.

4) Detection per Viewer Application: Table III and Figure 2 summarize and visualize all ILC detections and present the detection rates per PDF viewer. Note that these rates are heavily depending on the sample set, and do not necessarily reflect the quality of the PDF viewers or the number of exploits that exist for them in the wild. What definitely can be seen, is the unsurprising fact that combining the partial results of our detection scheme yields a higher detection rate. Furthermore, it is obvious that each single PDF viewer instance is vulnerable to a significant amount of malicious PDFs. One single exception to this is the *Foxit Reader*. Since this application is not nearly as widespread as the *Acrobat Reader*, not much effort has been invested by attackers into building exploits for it. Accordingly, the very low detection rate for this viewer does not necessarily mean that it has less critical software bugs.

5) Detection Results of Other Analyzers: In order to evaluate the effectiveness of our solution, we compared our results against those from the popular application specific analyzers *Wepawet* [19], *PDF Examiner* [20] and *ADSandbox* [21]. All of these analyzers combine static and dynamic approaches, i.e., they parse the PDF document structure, extract potential malicious pieces and then analyze them by different means. Depending on the severity of the findings, each analyzed sample is then labeled either *benign*, *suspicious* or *malicious*. Furthermore, additional comprehensive analysis data is generated, i.e., information about the embedded objects, like PE files or URLs, or contained known exploits.

Wepawet [19] combines machine learning techniques

TABLE III: Detections per Viewer

Viewer	Samples	Fraction
Foxit 3.0.0	17	0,25%
Adobe 6.0.0	2036	30,03%
Adobe 7.0.0	4592	67,72%
Adobe 7.0.7	4727	69,71%
Adobe 8.1.1	5355	78,97%
Adobe 8.1.2	4994	73,65%
Adobe 8.1.6	1941	28,62%
Adobe 9.0.0	4994	73,65%
Adobe 9.2.0	1974	29,11%
Adobe 9.3.0	1672	24,66%
Combined	6781	100,00%

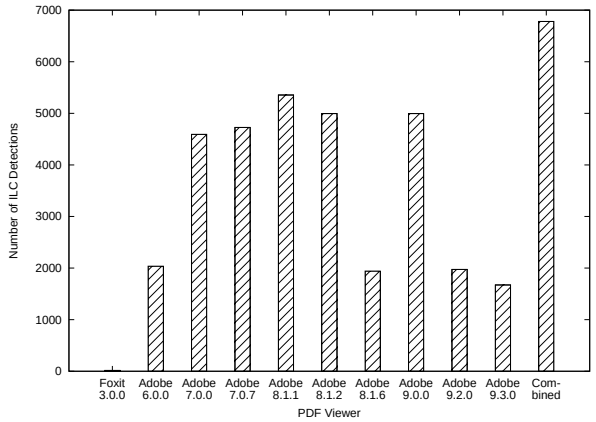

Fig. 2: Visualization of Detections per Viewer

with emulation. It extracts specific features while emulating Javascript code and then compares them against a set of previously learned known benign profiles. It also uses a set of signatures to detect anomalities, which are *not* based on Javascript. The author has supported our project by analyzing our samples with the new version of his tool, which currently is not available yet. A better detection rate in comparison to the current available version could be achieved with that.

PDF Examiner [20] as well extracts all embedded objects and streams from the PDF document and decrypts them if necessary. Then, signature scanning is used to detect known malicious patterns and *libemu* [12] is used to detect shellcode. From all the findings a score value is calculated, that decides about the ultimate outcome of the analysis. Besides this value, a sophisticated GUI report is generated that highlights suspicious and malicious parts of the PDF document.

In contrast to the two aforementioned analyzers, *ADSandbox* [21] solely aims at the detection of malicious Javascript. For that purpose, all Javascript code objects are extracted from a PDF sample and then executed in an isolated environment. Finally, heuristics are used to decide from the executed operations and the involved data about the maliciousness of the particular sample. ADSandbox can be used with several different configurations settings, but we have used the defaults for simplicity.

When comparing the results of such application specific analyzers to those created by *CWXDetector*, one have to take into account that our tool only triggers on the actual execution of ILC. Accordingly, it is only capable to label a sample as *benign* or *malicious*, but not as *suspicious*.

Table IV summarizes all results for the detection of malicious samples. Interestingly, our approach yields even better results than those of the application specific analyzers if only taking those samples into account which were labeled as being *malicious*. But still when considering also the suspicious samples, our results are comparable, i.e., 89.0% (Wepawet) and 98.9% (PDF Examiner) vs. 93.2% (*CWXDetector*). Furthermore, we know that a significant part of those malicious samples which have been not detected by *CWXDetector* are corrupted and, hence, not executable at all. A signature scanning based approach is obviously also able to detect malicious parts within those broken files, but our method obviously fails on them. ADSandbox does not deliver a very high detection rate on our malicious sample set since its main focus is to analyze Javascript only.

TABLE IV: Detection Results on Malicious Sampleset

	Malicious		Suspicious	
Analyzer	Samples	Fraction	Samples	Fraction
Wepawet	4,737	65.1%	1,739	23.9%
PDF Examiner	6,089	83.7%	1,108	15.2%
ADSandbox	2,360	32.4%	255	3.5%
CWXDetector	6,781	93.2%	0	0.0%

When it comes to the false positive rate, the comparison is rather simple (see in Table V). As described above our approach does not produce any false positive. Also the other three analyzers generate good results: 0 false positives for Wepawet as well as for ADSandbox. There is a trade-off in detection accuracy of PDF Examiner, since this detector has the best detection rate but also produces the most false positives of around 4.5%, which still is an acceptably low number.

D. Additional Experiments

In order to emphasize the universality of our approach we briefly present detection results from different

TABLE V: Detection Results on Benign Sampleset

	Malicious		Suspicious	
Analyzer	Samples	Fraction	Samples	Fraction
Wepawet	0	0.0%	0	0.0%
PDF Examiner	82	1.1%	246	3.4%
ADSandbox	0	0.0%	3	<0.1%
CWXDetector	0	0.0%	0	0.0%

applications. We have used *CWXDetector* to analyze malicious *Flash* documents as well as malicious network packets that exploit vulnerabilities in the *Real VNC viewer* and the *VideoLan Client (VLC)*.

1) Flash Documents: As additional example for shellcode containing documents we have analyzed two malicious *Flash* files. The first one was created with the help of the *Metasploit Framework*[31] and the other one was found in the wild and contained in the *Contagio Dump Archive*[32] and named *JOB_DESCRIPTION.doc*. Both samples exploit the *CVE-2011-0611* vulnerability of the *Flash Player* version 10.0.45 by executing an *ActionScript* that performs an invalid object type usage, resulting in arbitrary code execution. Since both *Flash* samples are embedded into a *Word* document, we have used *Microsoft Word Professional 2010* to actually open them.

Both samples were detected by our tool and in both cases the ILC containing memory pages were dumped. In the following we give a brief discussion of the findings from the real-world example. As in most cases all pages but the last ones contain a nop sled. The sled is built by the operation **adc [ecx], edx**, which is the assembly representation of the value 0x1111. After a huge amount of such instructions, the real shellcode starts by locating the required API functions. By walking the *Export Address Table* of the *kernel32.dll* module, the entry points of roughly a dozend system functions obtained, e.g. *LoadLibraryA*, *GetFileSize*, *CreateFileA*, *WinExec*, *CreateFileMappingA*, ...

The code then tries to locate the memory region into which the initial *Word* document was loaded, since besides the shellcode it also contains a second malware as well as a benign *Word* document that should be dropped. For that purpose **GetFileSize** is called with all possible handle values, starting from 0 and increasing it by a value of 4 for each iteration. A simple heuristic is used to identify the correct file by comparing the result value of **GetFileSize** with a minimum size of *0x7000*. The resulting handle is then used to create a memory section by calling *CreateFileMappingA* and *MapViewOfFile* for accessing the embedded objects easily.

After that two new files are created in the system's temporary folder and the embedded objects are copied to them. The first file is called *scvhost.exe*, which obviously should look similar to the Windows service host process *svchost.exe*. We have not performed a detailed analysis of this dropped file, but obviously it comes the real malware. After creation it is executed via the *WinExec* API. The second file is named *AAA* and in fact is a valid *Word* document without malicious content.

Finally, the *WinExec* API again is called to execute a batch of shell operations and the *Word* process is terminated. The shell operations first perform some delay, then overwrite the original *.doc* file with the dropped *AAAA* file and then load it into a new *Word* instance.

2) VNC Client: The traditional way to inject shellcode into systems has been to embed it into network packets and exploit vulnerabilities in the parsing server application. Only the increased awareness and improved security of contemporary server applications and operating systems has driven the attackers to shift to malicious documents. In order to illustrate the effectiveness of our generic approach we show that it is capable to detect malicious code execution also in this context. Therefore, we have used the *Metasploit Framework* to setup a network server that accepts connections from remote *VNC* clients. After executing the *RealVNC client version 3.3.7* in combination with our *CWXDetector*, we connected to that server and received a specially crafted network packet. This packet contains an exploit for the *CVE-2001-0167* vulnerability of the *RealVNC* application. Of course, *CWXDetector* detects the execution attempt of the first contained shellcode instruction and dumps the related memory to a file. Since we have created the shellcode on our own and it only contains the functionality to show a small user dialog it does not make any sense to further analyze it here.

3) VideoLan Client: One additional analysis of a network application exploited by a malicious network packet was performed with help of the *CVE-2010-3275* vulnerability, which exists in the versions 1.1.4 up to 1.1.7 of the *VideoLan Client* (VLC). By accessing a specially crafted *.amv* file, VLC can be crashed by the usage of an invalid pointer and arbitrary code can be executed. With the help of *Metasploit* we again have set up a web server that generates such a malicious data and offers it over the network for downloading. Unsurprisingly, our detection mechanism triggers again and extracts the malicious instructions once the embedded shellcode is about to be executed.

VII. Extraction Evaluation

In this section we try to measure the *quality* of the extracted shellcode chunks. To that purpose we determine the percentage of contained x86 instructions (*code ratio*) and the amount of data in terms of embedded strings (*data ratio*). Since shellcode often uses encryption and code obfuscation to avoid detection, we expect only poor *quality* when investigating the initially created dump files. To encounter this problem, we had applied the MVD feature described in section III-E. With that functionality, additional dump file versions are created when memory is modified, e.g. self-modifying code is executed. By considering the final version of a dumped memory page, chances are high to get a fully decrypted version of the shellcode. By further comparing it with the initial dump, one can easily identify the modified code parts.

Our original PDF analysis from section VI has been done without the MVD feature, because it increases the size of the resulting data enormously. Accordingly, we had to perform another experiment, now with MVD enabled. In order to reduce the amount of information that has to be examined afterwards, we have only used a subset of the malicious PDF documents and used only one particular PDF viewer. In fact, we have chosen the *Adobe Acrobat Reader 9.00* and those 4,869 samples, for which ILC execution has been detected in that PDF viewer in the first experiment.

A. Quality of Shellcode Chunks

Obviously, we are not able to manually examine all the dumped files and also have no way to actually understand the semantics of shellcode in an automated way. Therefore, we measure their *quality* by the percentage of valid x86 instructions (*code ratio*) and the amount of contained strings. To that end, we have utilized the *IDA Pro Disassembler*[33] to measure the percentage of bytes from each dump that can be disassembled correctly. There are several problems with that proceeding. On the one hand, shellcode often uses indirect and obfuscated control transfers, which disturbs the correct operation of a disassembler. On the other hand, also random binary data can be disassembled into valid x86 instructions to some amount. However, we are aware that the resulting code ratio is only a rough approximation of the real code amount, but it enables us to analyze several ten thousand dumped instruction chunks in an automated way. Besides the code, we also try to measure the amount of valid data, namely the contained strings. Therefore, we have identified and counted all strings from the dumps and applied some easy heuristics to restrict the resulting set to only obvious valid ones, e.g. we only kept those with a length greater than 8 or those which contain special keywords like *.exe* or *.dll*.

B. Shellcode Partitions

We have not examined each dumped page separately, but we have concatenated all consecutive pages to partitions first. One advantage of this concatenation is that it mitigates the effect of the fact that on x86 architecture there is no memory alignment required for instructions. If a particular operation is placed on a page boundary, it gets split when each page is dumped separately. If multiple versions of the same page were dumped during analysis, we only examine the initial and the final one. By comparing them with each other, we are able to evaluate the effectiveness of our automated unpacking technique by comparing the amount of valid code and contained data. The example in Figure 3 shows that ILC execution was detected in five different pages. Therefore, all of them have been dumped on the initial detection. Page *III* has been modified twice and, accordingly, two additional dump files were created that contain the modified version of the memory content. After the analysis is finished, all consecutive pages are concatenated into partitions. Partition *A* contains the pages *I*, *II* and *III* and partition *B* the pages *IV* and *V*. Since there is a multiversion page in partition *A*, two different versions of it are created: one that contains all the initial versions of the dumps (*partition_A_initial*), and another one with the final version of each page (*partition_A_final*).

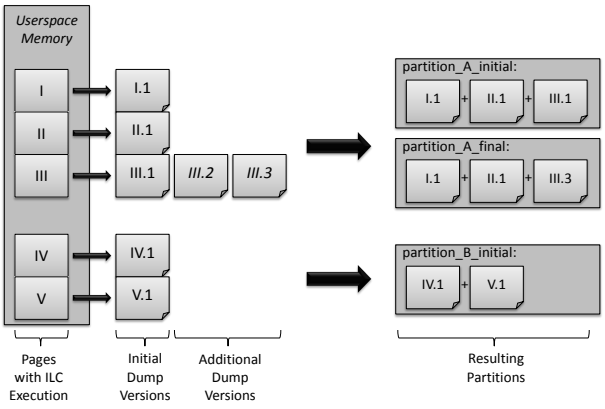

Fig. 3: Dumps and Partitions

C. Discussion

In particular we have performed the following steps to measure the quality of the extracted ILC:

- we analyzed 4,869 PDF samples in *Acrobat Reader 9.00* with enabled MVD,
- all consecutive memory pages were concatenated to partitions, resulting in either one or two versions each:
  - one *initial partition*, if only one dump version of each contained memory page exists,
  - and additionally one *final partition*, if more than one dump version exists for at least one contained page
- the code ratio of each partition was determined by using *IDA Pro*, and
- all valid strings from each partition were extracted and counted.

We then selected those partitions for which an initial *and* a final version existed, i.e. those which contain self-modifying code. We found 2,534 partitions of this kind. Figure 4 illustrates the code ratio for the initial and final partitions respectively. One can easily see that the percentage of valid instructions increases dramatically when applying the MVD feature. Figure 5 shows the improvement of the data ratio - in terms of valid strings - when the shellcode is automatically unobfuscated. When compared with the code ratio the bettering is only marginal. Nevertheless, in sum we extracted 7,807 strings and 1,866 URLs from the initial partitions, and 8,676 strings and 2,280 valid URLs from the final ones.

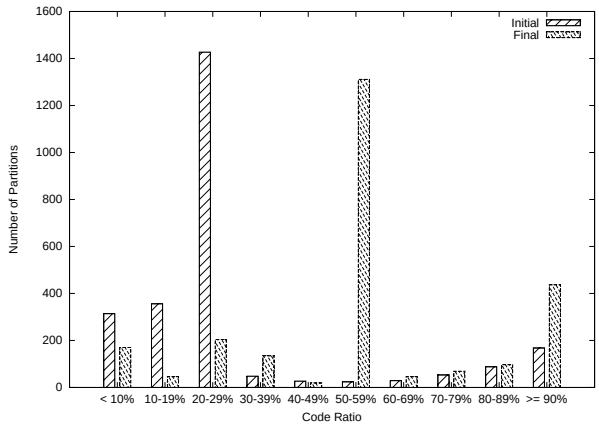

Fig. 4: Distribution of Code Ratio

VIII. Conclusions

In this paper we presented a generic and automatic method to detect and extract illegitimate code. We presented *CWXDetector*, an implementation of our approach for the x86 Windows XP version, and evaluated it by analyzing a large corpus of malicious PDF documents. Our system turns out to be very effective in supporting malware analysis, since the detection rates are very good and it directly supports the analyst by extracting a small set of memory pages for manual inspection. This further inspection has not been part of our work and opens new fields of investigation. Especially the contained URLs and server host addresses that point to additional malware sites are valuable resources. Furthermore, the insights gained by a post processing analysis may assist in developing new protection techniques and creating signatures for zero-days until patches are available. We have also shown how the quality of the extracted ILC can be increased dramatically by applying multi-version dumping to automatically deobfuscate it.

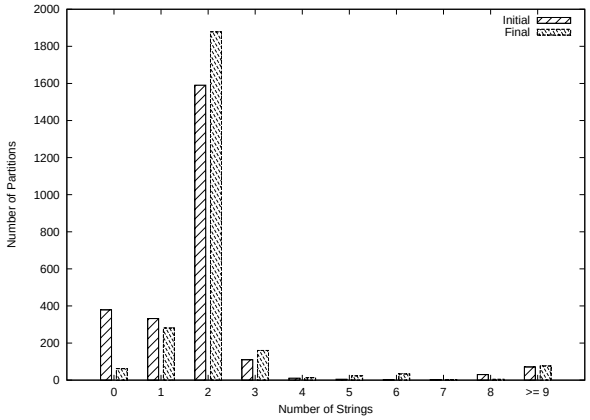

Fig. 5: Distribution of Data Ratio

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APPENDIX

We now present more details on the Windows-based implementation from Section IV. We first present the details of the hook functions used by *CWXDetector*.

The hook of **NtAllocateVirtualMemory** first checks the caller and the wanted memory protection. If the caller is *not* trusted, that protection value is modified such that the allocated memory becomes non-executable. Then the original system service is invoked to actually perform the allocation operation. All this happens transparently to the caller, i.e., no error result is returned in case of a modified protection parameter.

The proceeding within the **NtProtectVirtualMemory** hook is rather similar. Again, for all untrusted callers the protection parameter is manipulated to being non-executable. Since this system service can be used to modify the protection settings of already loaded modules, we also have to intercept when it is invoked by trusted callers. In that case it is first checked if the affected module belongs to a trusted file or not. If it is not trusted, the protection value again is modified to non-executable. The reason behind this is to block the execution of untrusted files.

The hook function of **NtMapViewOfSection** ensures that after mapping a file into address space, all containing memory fulfills our requirement. Since we cannot simply modify a call parameter like within the previously mentioned hook functions, but have to operate directly on the VAD [4] respectively PPTE entries, the hook first calls the original system function. After that, different actions are performed, depending on the fact if a data or an image file was mapped.

For image files the effective page protection is taken from the related PPTE. Therefore, our hook enumerates all executable subsections of the related segment object and manipulates their PPTEs. In case of trusted files, only those PPTEs are modified which also indicate writable memory. In such case the PPTEs remain writable, but are no longer executable. Otherwise it would be possible for an attacker to modify the instructions which are contained in memory that is associated with legitimate code. By removing the execution property, an attacker is still able to modify it, but we detect the approach to ultimately execute the overwritten instructions. In general, a PE file should never contain executable sections which are also writable, but due to the procedure described above we are able to detect those as well.

If a data file is mapped, the situation is a bit different. For those kind of files the effective protection setting is taken from the associated VAD entry. When the related memory is actually accessed, the PTEs are created and their protection settings are directly taken from the VAD. Therefore, again we check if the section belongs to a trusted file or not. If it belongs to an untrusted file, the VAD is modified to *non-executable*. If it is trusted, the VAD protection is only modified if it is writable *and* executable.

In addition to Section IV-B, we now present additional details on how we check the caller. Figure 6 shows an example to illustrate the relationship between the usermode stack layout and trapframe values, when performing a system call. The native API functions **KiFastSystemCall** and **NtCreateFile** use *frame pointer omission* (FPO), which means that they do not set up a full stack frame. Therefore, the saved frame pointer EBP cannot be used to locate their saved return addresses on the stack. Nevertheless, those saved RET addresses can be obtained from the raw usermode stack by inspecting the slots pointed to by the stack pointer ESP and ESP+4. As shown, the first usermode function with a full stackframe can be reached via the saved EBP. All further calling functions can then be enumerated by using the saved EBP values, as long as they do not perform FPO. In that case we would have to involve additional information about the function's prototype and local variable area in order to further enumerate the stack frames. However, all trusted callers we are using in our experiments set up a full stack frame.

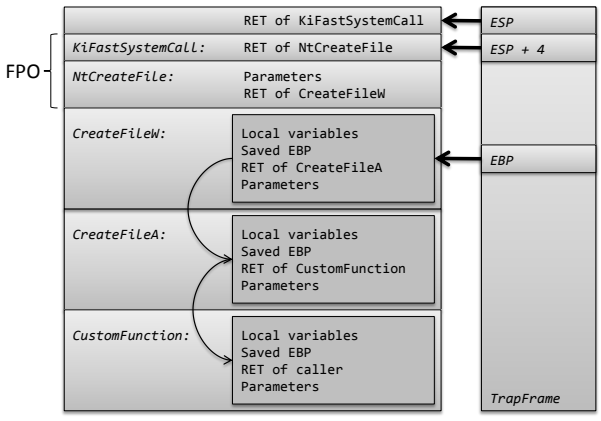

Fig. 6: Stack Frames and Trap Frame

In order to verify that extracted ILC dumps really consist of shellcode, we have used different methods. One was to identify known shellcode instruction pat-

terns, which have been gathered from different sources. Besides our experiences from other work in the past, we also have analyzed the Windows shellcode stubs from the *Metasploit Framework*[31], and we have manually analyzed all instruction sequences that have been dumped by our system and that did not contain any of the already known patterns. Examples of those patterns are:

- GetPC heuristics, e.g. **jmp/call** or **fsetenv**
- Memory Scanning techniques, e.g. directly calling the system function **NtAccessCheckAndAuditAlarm** with the **int 0x2e** instruction (*Egg Hunting*)
- very long nop-sleds followed by valid code

Some malicious documents use built-in features to start a new process while using specially crafted parameters in order to exploit it. We have seen three different applications that have been started in such way: *Internet Explorer (iexplore.exe), Outlook Express (msimn.exe)* and the *Command Shell (cmd.exe)*. Two examples of the used malicious parameters are shown in Figure VI. Looking at these parameters it indeed seems that these documents are malicious.

We have seen a lot of known malicious PDF documents that failed to execute ILC, but instead presented some user dialog. Those dialogs can be either an error message as a result of a broken PDF document or it can be a specially crafted dialog which is shown on behalf of the PDF document itself. Table VII presents some of the most seen dialog messages.

The processes which have been started by the malicious PDF documents fall into three classes: it is either tried to perform malicious operations from within a second extracted or downloaded malware, to open a benign PDF document in order to hide the maliciousness of the initial document or to gather essential information about an exploited system. Table VIII enumerates examples from each of those three classes.

```
mailto:
%/../../../../../Windows/system32/cmd".exe"" /c /q \"@echo off
&netsh firewall set opmode mode=disable&echo o 127.0.0.1>1
&echo binary>>1&echo get /ldr.exe>>1 &echo quit>>1
&ftp -s:1 -v -A>nul&del /q 1 &start ldr.exe&\" \"&\" "nul.bat
```

```
mailto:
%../../../../../windows/system32/mshta"" javascript:e=String.fromCharCode;
new ActiveXObject\('wscript.shell'\).Run\('cmd /c for /F %i IN
\('+e\(39\)+'dir /b/s %Tmp%or~1\\\\content.ie5\\\\*.pdf'+e\(39\) +'\)
DO findstr /B CZY %i>c:/a.vbs&c:/a.vbs',0\);\.close\(\)//.cmd)
```

TABLE VI: Malicious Process Parameters

PDF parsing error messages:

- A 3D data parsing error has occurred
- An unrecognized token 'aaaaaaaaa' was found
- The application is being terminated because of memory corruption

JavaScript errors messages:

- line 3 - GeneralError: Operation failed
- var ZUl8cVPKM33; var MpuldZ90lGs = new Array(); ...

Failed exploitation attempt messages :

- The application "C:\AAAAA..." is set to be launched by this PDF file...
- Could not open the file '/C/AAAAAAA AAAAAAAAAAAAAAAAAAAAA...

TABLE VII: Dialog Messages of Malicious Samples

Obviously malicious processes:

- c:\a.exe
- c:\DOKUME~1\user\LOKALE~1\Temp\HotPAtcher.exe

New instances of the PDF viewer:

- c:\Programme\Adobe\Acrobat7.0\Reader\AcroRd32.exe"c:\DOKUME~1\user\LOKALE~1\Temp\ASA2010.final1.pdf"
- cmd.exe/cstartAcroRd32.exe"c:\DOKUME~1\user\LOKALE~1\Temp\1465.pdf"

Common Windows system information tools:

- c:\WINDOWS\system32\winver.exe
- c:\WINDOWS\system32\whoami.exe

TABLE VIII: Started Processes