Reuse-Oriented Camouflaging Trojan: Vulnerability Detection and Attack Construction

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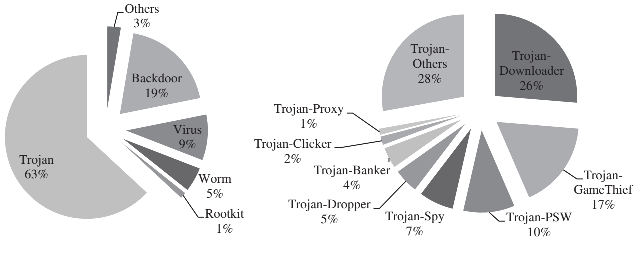
Abstract

We introduce the reuse-oriented camouflaging trojan – a new threat to legitimate software binaries. To perform a malicious action, such a trojan identifies and reuses an existing function in a legal binary program instead of implementing the function itself. Furthermore, this trojan is stealthy in that the malicious invocation of a targeted function usually takes place in a location where it is legal to do so, closely mimicking a legal invocation. At the network level, the victim binary can still follow its communication protocol without exhibiting any anomalous behavior. Meanwhile, many close-source shareware binaries are rich in functions that can be maliciously "reused", making them attractive targets of this type of attack. In this paper, we present a framework to determine if a given binary program is vulnerable to this attack and to construct a concrete trojan if so. Our experiments with a number of real-world software binaries demonstrate that the reuse-oriented camouflaging trojans are a real threat and vulnerabilities of this type in legal binaries can be effectively revealed and confirmed.

1 Introduction

Trojan is the type of malware that appears to perform a desirable function but actually contains malicious logics. It has been a major threat to software security and reliability. According to our study of malware samples in *VxHeaven* [5], trojans remain a dominant malware category. As shown in Fig. 1(a), trojans account for 63% of all 266980 malware samples, whereas the shares of virus, worms, and rootkits are 9%, 5%, and 1%, respectively. The diverse payload of trojans is shown in Fig. 1(b). Another study by BitDefender [1] shows that, from January to June 2009, trojan malware is on the rise, accounting for 83% of the global malware detected in the wild.

Most existing trojans are implemented as *new, independent pieces of code*. In this paper, we demonstrate that trojans can be more stealthily constructed by *reusing* functions from existing, third-party software binaries. We call such attacks on existing binaries *Reuse-Oriented Camouflaging* (or ROC for the rest of the paper) attacks. Moreover, we show that real-world software binaries may be vulnerable to ROC attacks and we define such vulnerability as the *ROC vulnerability*. We demonstrate that the detection of ROC vulnerabilities as well as the construction of ROC attacks (i.e., creation of ROC trojans) for confirming the vulnerabilities are not only feasible but can be made highly systematic.



(a) (b)

Figure 1. Distribution of (a) malware types and (b) trojan payloads in VxHeaven.

The key observation behind ROC attacks is that certain functional features in legal software binaries can be subverted for malicious purposes. For example, an FTP program has all the basic capabilities to steal and transfer privacy-sensitive files; an email client has all the functions to send spams. For a ROC trojan for spamming, the subject and content of a spam message could be supplied to the proper mail-sending function, which will then send out the message just like a regular email. The attacker does not have to perform any environment setup such as socket creation, hand-shaking, and payload encoding.

ROC trojans have unique properties. In particular:

- Statically, they do not have a *stand-alone* code body that implements the malicious semantics. In comparison, traditional code injection attacks or persistent software parasites [6] usually require injecting a piece of code to the victim program and the injected code often manifests rich, distinct footprint that can be used to detect such code. In a ROC attack, since the malicious semantics is fulfilled by reusing existing functions in the victim binary, the attack only needs to apply a simple patch with a few writes to memory re-

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gions that correspond to *legal* variables in the original binary. These writes could be indistinguishable from the existing writes in the binary.

- Dynamically, the runtime behavior of the binary under attack complies with constraints dictated by the program semantics. The attack is mostly carried out by manipulating program states and duplicating existing function invocations. The duplicated "malicious" function invocations occur at a place where it is legal to do so.
- Furthermore, since the attack reuses communication protocol implementation in the binary, from the network's perspective, the victim binary could still follow the communication protocol without exhibiting any anomalous behavior.

A typical scenario of launching a ROC attack is as follows: The attacker downloads the binary of a popular close-source freeware (e.g., a P2P sharing or streaming program) and then patches it with logic for malicious reuse of legitimate function(s). According to a study on how the top 100 malware programs in 2008 infect computers [4], the patched binary (i.e., the ROC trojan) could be disseminated by the attacker via a number of ways: downloaded (without user consent) from the Internet which accounts for 53% of malware infection; dropped by other malware (43%); through email attachments (12%), browser iframe compromises (7%), software vulnerabilities (5%), and so forth.

ROC attacks are likely to succeed considering (1) the prevalence of "*drive-by downloads*" and the wide existence of stealthy downloading malware (e.g., the trojan-downloader in Fig. 1(b)) and (2) the lack of universal binary integrity checking infrastructure for many close-source shareware programs today. Meanwhile, many close-source shareware programs are rich in functions that can be reused for malicious purposes, making them attractive targets of ROC attacks.

To illustrate the real threat of ROC attacks, we propose a systematic framework for detecting ROC vulnerabilities: Given a close-source binary, our framework will identify ROC vulnerabilities in it and further construct a ROC trojan to confirm the true existence of the vulnerability. Our framework also serves the purpose of demonstrating the feasibility of ROC attacks and thus raising public awareness. The detection of ROC vulnerabilities involves two main steps:

- **Step I – reuse-able feature extraction**. Given a subject binary and its output that can be used in malicious contexts (e.g., an email client and the emails it sends out), our framework will check if modular functions exist which are dedicated to producing that output. Such functions are potential targets of malicious reuse if their execution leads to very few *reversible side-effects*. For example, the email client logs emails sent in the sent-email folder – a side-effect that should be reversed for a spammer. Our framework employs dynamic binary analysis techniques to narrow down the reuse-able functions and quantify their side-effects.
- **Step II – reuse-able function argument identification**. The key part of a ROC attack is the malicious setup of parameters to invoke the reuse-able feature function. We show that it is possible to identify such arguments *without* source code and symbolic information. Our framework adopts a runtime program state diff-ing approach, which involves running the subject binary twice – with the same setting but different input value assignments. The differences in the two resulting memory states will reveal a wealth of information about the arguments of the reuse-able function, including their memory regions and reference paths.

Our framework also includes a ROC attack composer. To implant malicious logic, reusable function invocations in the original binary are patched to expose critical internal states and allow mutation. Such functions and states are identified by the ROC vulnerability detector. If needed, function invocations can be duplicated in the same context of the original invocation such that the semantic constraints imposed on legal calling of the target function are satisfied, i.e., the legal calling context is maliciously reused. We provide API functions to enable easy ROC attack composition. Non-trivial attacks can be constructed by writing a few lines of code, which will be translated into binary and patched into the victim binary.

We have implemented a prototype of the ROC vulnerability detector and attack composer and applied them against a number of real-world binaries. Our experiments show that ROC attacks are real and easy to construct. For example, the email client `pine` and `mailx` can be converted into a stealthy email interceptor; the P2P software `Mutella` can be exploited to perform covert Command and Control (C&C) for a botnet; and the P2P software `gift` can be converted to transfer sensitive files to other hosts without being noticed.

2 Approach Overview

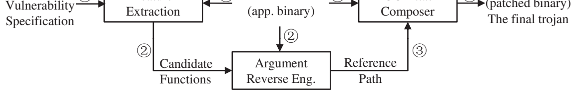


Figure 2. Typical workflow of ROC vulnerability detection and attack construction.

Fig. 2 illustrates a typical workflow of ROC vulnerability detection and attack composition. Given a target binary, the user will first specify a *desirable* ROC vulnerability. Unlike traditional "syntactic" vulnerabilities such as buffer-overflows, ROC vulnerabilities are highly dependent on the victim program's *semantics*, namely the program's functional feature that can be reused in a malicious context.

Using the desirable vulnerability (feature) specification as input, the *feature extraction* component automatically identifies a set of candidate functions to reuse. The best candidate function is the one that leads to the least amount of side effects. The functions' side-effects are quantified by the *side effect analysis* component. Meanwhile, the *argument reverse engineering* component identifies the memory locations of the functions' arguments. The output of this component is a *reference graph*, which presents a hierarchical view of the memory for the argument variables. Finally, using the outputs of *side-effect analysis* and *argument reverse engineering*, the *ROC attack composer* generates the actual malicious patch that invokes the best reuse-able function.

3 ROC Vulnerability Detection

3.1 Specifying ROC Vulnerabilities

Since we assume neither the source code nor in-depth understanding of a victim binary, the only thing we can leverage to define a functional feature is the input and output of the software. In many cases, the input/output does provide a lot of information about the relevant features. For instance, if we want to decide if the email sending feature of `pine` can be exploited, the email messages emitted by `pine` can be used to trace back to the functions that are responsible for sending them. As another example, if we want to detect whether the file transfer feature of a P2P client is vulnerable, we can annotate the network packets generated by the file transfer protocol. With the annotations, the functions corresponding to file transfer can be disclosed by execution monitoring.

To generalize the above examples, our approach to ROC vulnerability specification is *to represent candidate features of software by identifying the output generated (the input processed) by these features*. The specified output (input) often follows standard formats that can be inferred from high-level knowledge about the software. More formally, we consider the output (input) as a sequence of bytes and the relevant output (input) as a sub-sequence. The sub-sequence is described by a grammar $\mathcal{G}$. The corresponding parser filters the irrelevant output (input). To use our ROC vulnerability detection components, the user only needs to provide the grammar $\mathcal{G}$. For instance, the grammar of email messages can be easily derived from RFC-2822. The generated parser is responsible for recognizing the relevant output and parsing it into fields (nonterminals). As to be shown, such fields will be used to compose ROC attacks.

$$\begin{array}{rcl} \mathit{Message} & \rightarrow & \mathit{Header}\ \mathit{Body} \\ \mathit{Header} & \rightarrow & \mathit{Subject}\ \mathit{Receiver}\ \mathit{Sender} \\ \mathit{Receiver} & \rightarrow & \mathit{Addr}^{+} \\ \mathit{Sender} & \rightarrow & \mathit{Addr} \\ \mathit{Title} & \rightarrow & \mathit{String} \\ \mathit{Body} & \rightarrow & \mathit{String} \end{array}$$

Figure 3. Simplified grammar $\mathcal{G}$ of email messages, provided as the input to the ROC vulnerability detector.

A sample output grammar provided to our detector is shown in Fig. 3. It is to detect ROC vulnerabilities in `pine` regarding the email sending feature. It is a simplified version for sake of presentation. A full grammar can be found in RFC-2822.

3.2 Detecting ROC Vulnerabilities

This section describes how the detector works given the specification described in the previous section. For brevity, our discussion in this section focuses on *output* based specification, i.e., $\mathcal{G}$ is a grammar that filters output. Handling input-oriented ROC vulnerabilities is similar and examples of input-oriented ROC vulnerabilities can be found in Section 5.

3.2.1 Feature Extraction

Given a grammar $\mathcal{G}$ describing an output sub-sequence, *feature extraction* identifies the set of modular functions in the binary that are exclusively dedicated to the task of manipulating and emitting the output described by $\mathcal{G}$. Other less dedicated functions are less vulnerable as subverting them may cause unexpected effects. For example, the function `sendpacket` is used by multiple features in `pine` including sending emails and communicating with email servers. The function is not vulnerable to ROC attacks regarding email sending because subverting the function would introduce undesirable effects for all the services relying on it.

Feature extraction is mainly carried out by profiling. Let o be the output sub-sequence accepted by $\mathcal{G}$ and o_i represent the ith byte of o. Our technique instruments the binary to support a mapping from an observed byte to the definition point of the byte, represented as pc_i, meaning the ith instance of the instruction at pc during execution. The instrumentation is via standard dynamic program dependency tracking (namely taint analysis), which has been widely used in data life time tracking [13], exploit detection (e.g., [25]), malware analysis (e.g., [30]), and so on. In particular, we instrument each memory read, write, data movement, and data arithmetic, to catch dependencies between data definition and usage. We also capture the call stack context of data definition and usage.

The next step is to analyze the binary's executions to identify functions that are dedicated to producing the relevant output. In our solution, given an execution E whose relevant output is o, a dynamic call tree is constructed, with a node representing a dynamic function instance and an

Content	Call Tree Paths (Calling Contexts) of Definitions
`EHLO [10.0.0.4]\r\n`	...call_mailer→smtp_open_full→smtp_ehlo→sprintf→vsprintf→vfprintf→_IO_default_xsputn
`RSET\r\n`	...call_mailer→smtp_mail→smtp_send→0x804ad38→strcpy
`MAIL FROM:<alice@bob.com>\r\n`	...call_mailer→smtp_mail→smtp_send→0x804ac58→sprintf→vsprintf→vfprintf→_IO_default_xsputn
`RCPT TO:<alice@bob.com>\r\n`	...call_mailer→smtp_mail→smtp_send→0x804ac58→sprintf→vsprintf→vfprintf→_IO_default_xsputn
`DATA\r\n`	...call_mailer→smtp_mail→rfc822_output→post_rfc822_output… →pine_header_line→0x804ac58→sprintf→...
`Date: Wed, 22 Oct 2008 14:00:...`	...call_mailer→smtp_mail→rfc822_output→post_rfc822_output… →pine_header_line→fold→sstrcpy
`From: Alice <alice@bob.com>\r\n`	...call_mailer→smtp_mail→post_rfc822_output→pine_rfc822_output→pine_rfc822_header→pine_address_line
`X-X-Sender: alice@bob.com\r\n`	...call_mailer→smtp_mail→post_rfc822_output→pine_rfc822_output→pine_rfc822_header→pine_address_line
`To: bob@alice.com\r\n`	...call_mailer→smtp_mail→post_rfc822_output→pine_rfc822_output→pine_rfc822_header→pine_address_line
`Subject: a test\r\n`	...call_mailer→smtp_mail→rfc822_output→post_rfc822_output… →pine_header_line→fold→sstrcpy
`Message-ID: <Pine.LNX.`...`137@lo...`	...call_mailer→smtp_mail→rfc822_output→post_rfc822_output… →pine_header_line→fold→sstrcpy
`Content-Type: TEXT/` ... `format=...`	...call_mailer→smtp_mail→post_rfc822_output→pine_rfc822_output→pine_rfc822_header→pine_address_line
`aaaaaaaaaaaaaaaaaaaaaaaaa\r\n`	...call_mailer→smtp_mail→rfc822_output→post_rfc822_output… →gf_local_nvtnl→gf_terminal→l_putc
`.\r\n`	...call_mailer→smtp_mail→smtp_send→0x804ad38→strcpy
`QUIT\r\n`	...call_mailer→smtp_close→smtp_send→0x804ad38→strcpy

Table 1. An email string and the call tree paths to function instances that define the individual string.

edge $f \rightarrow g$ representing a dynamic invocation from f to g. Note that it is a tree instead of a graph as dynamically one callee instance has only one caller instance. Each byte o_i in o is then annotated on a node in the dynamic call tree if o_i is defined in the function instance represented by that node.

A function instance f is called a *containing function* of o if it is the common ancestor of all the function instances annotated. Intuitively, it means the entire o is defined inside f, either directly in f or in function instances transitively invoked by f. Note that if f is a containing function, its ancestors in the dynamic call tree are also containing functions. For example, suppose we want to subvert the email sending feature in `pine`. Email messages are annotated as the relevant output of `pine`. Table 1 shows a sample email and the paths in the dynamic call tree that lead to function instances that define individual bytes in the email message. These paths correspond to the calling contexts of the definition points. Consecutive bytes with the same path are aggregated and shown in column `Content`. Note that the call paths are partial as they all share the same prefix `main`→`compose_mail`→`pine_send`→`call_mailer`. According to the above definitions, `call_mailer`, together with `pine_send`, `compose_mail`, etc., are containing functions.

Not all containing functions are vulnerable. We exclude functions that can be invoked in executions that do not produce the relevant output. Let the set of containing functions for an execution E be $\mathcal{CF}(E)$, and the set of functions invoked by an execution E be $\mathcal{F}(E)$. Assume a test suite $\mathcal{T}$ with $\mathcal{T}^{\mathcal{G}}$ being the set of executions that manifest the relevant output. The set of feature functions is computed as follows.

$$\mathit{feature}(\mathcal{G}) = \bigcap_{E \in \mathcal{T}^{\mathcal{G}}} \mathcal{CF}(E) - \bigcup_{E \in \mathcal{T} - \mathcal{T}^{\mathcal{G}}} \mathcal{F}(E)$$

That is, the set of feature functions include the common containing functions shared by all cases that produce the relevant output – *excluding* those that do not produce the relevant output in some case(s). In the `pine` example, `compose_mail`, `pine_send`, and `call_mailer` are the feature functions. Function `main` is not part of the feature as it occurs in executions that do not send emails.

3.2.2 Side Effect Analysis

ROC attacks aim to reuse existing application logics implemented in modular functions to achieve malicious goals. They often entail duplicating calls to feature functions in their original context. One of the necessary conditions is that the function invocation to be duplicated has to have no or very few side effects. Otherwise, benign execution will get perturbed and stealth cannot be preserved.

Therefore, the next step of ROC vulnerability detection is to analyze the side effects of the functions in the feature we extract in the previous step. In this work, *a side effect* of a function instance is defined as a memory write in the function instance and the written value is used after the function instance returns; or a library call that results in observable external behavior (e.g., update to a log file). Writes to stack variables in the frame of a function instance f or to heap structures allocated and then freed inside f do not induce any side effects. The analysis is implemented by tracing memory writes, system calls, heap allocations and de-allocations.

Applying side effect analysis to `pine`'s feature shows that the functions in the feature all have side effects. As shown in Section 5, methods `compose_mail` and `pine_send` have a large number of side effects. In contrast, a maximum of 18 writes to global variables and a maximum of 9 heap allocations are observed as the side effects of `call_mailer`. They can be reversed by restoring the values of the updated memory locations. Therefore, we consider `call_mailer` as potentially vulnerable. In comparison, some side effects are not reversible like GUI displays. Functions having such side effects are not vulnerable (namely not maliciously re-usable).

3.2.3 Reverse-Engineering Critical Arguments

After identifying feature functions and excluding those with irreversible side effects, we have narrowed down the vulnerable functions to a small set. To decide whether they are truly vulnerable, we need to check if the behavior of these functions can be mutated by changing program state. Therefore, the last step in ROC vulnerability detection is to identify critical arguments of these feature functions. Without loss of generality, we consider one feature function f in this section.

The ROC vulnerability detector relies on checking two conditions. One is to *identify the important variables (memory regions) whose values need to be modified in order to manipulate the specified output*. For example, email redirection entails finding the memory region that stores the recipient's email address. The other condition is to *identify the reference paths to these variables (memory regions)*. A variable or a memory region cannot be accessed simply through their absolute addresses, which may change from run to run. Therefore, an attack cannot be constructed (and hence f is not vulnerable) unless a reference path that consistently leads to the same variable (memory region) across all runs can be identified.

Our ROC vulnerability detector identifies critical memory regions through *memory differencing*. We obtain an extra *execution* by changing some of the program inputs and directing the software to produce different outputs. The original execution is called the *reference execution*. The memory snapshots of the two executions at the invocation of the feature function f are compared to isolate the relevant memory regions. For example, in the `pine` case, the reference execution sends a message to an address x, whereas the extra execution is acquired by sending the same message to a different address y. The memory states before the invocations of `call_mailer` in the two runs are compared to identify the memory region that stores the recipient address, which should be the only difference of the two runs. Recall that `call_mailer` is the candidate vulnerable function identified in the previous phase.

In practice, a dynamic data structure d may be allocated to different locations in the two runs. Comparing the same memory location (of d in one run) in both runs may lead to the wrong conclusion that d does not hold the same value in the two runs. To properly compare two memory snapshots, we need to construct the correspondence between memory cells. We define the problem as a *memory alignment* problem. More formally, *given two executions E and E' and a memory variable i in E, the memory alignment function identifies a memory variable in E' that corresponds to i*. The function is denoted as $\mathcal{MA}_{E \to E'}(i)$, or $\mathcal{MA}(i)$ for short if the two executions are clear from the context. $\mathcal{MA}(i)$ is a partial function, for i that does not correspond to any memory variable in E', $\mathcal{MA}(i)$ is undefined, denoted as $\mathcal{MA}(i) = \perp$.

Theoretically, memory alignment is an undecidable problem. We propose an approximate solution based on *Reference Graph* (RG). Intuitively, RG identifies reference paths to all live memory regions. For any live memory region, there must exist a reference path starting from a global variable, a stack variable on the current frame, or a register. Hence the roots of an RG have to be one of the above three types of variables. The RG serves as an indexing scheme over the memory space so that indices can be used to identify memory alignment. The formal definition of RG is as follows.

`Subject: SPAM`	`Subject: Hello`
`From: <alice@bob.com>`	`From: <alice@bob.com>`
`To: bob@alice.com`	`To: bob@alice.com`
`This is a spam email.`	`Hello, world`

Table 2. The two different test emails

Definition 1 *A reference graph is a pair $\langle N, E\rangle$ with N being the set of nodes and E being the set of edges. A node represents a memory region or a field. There are two types of edges.*

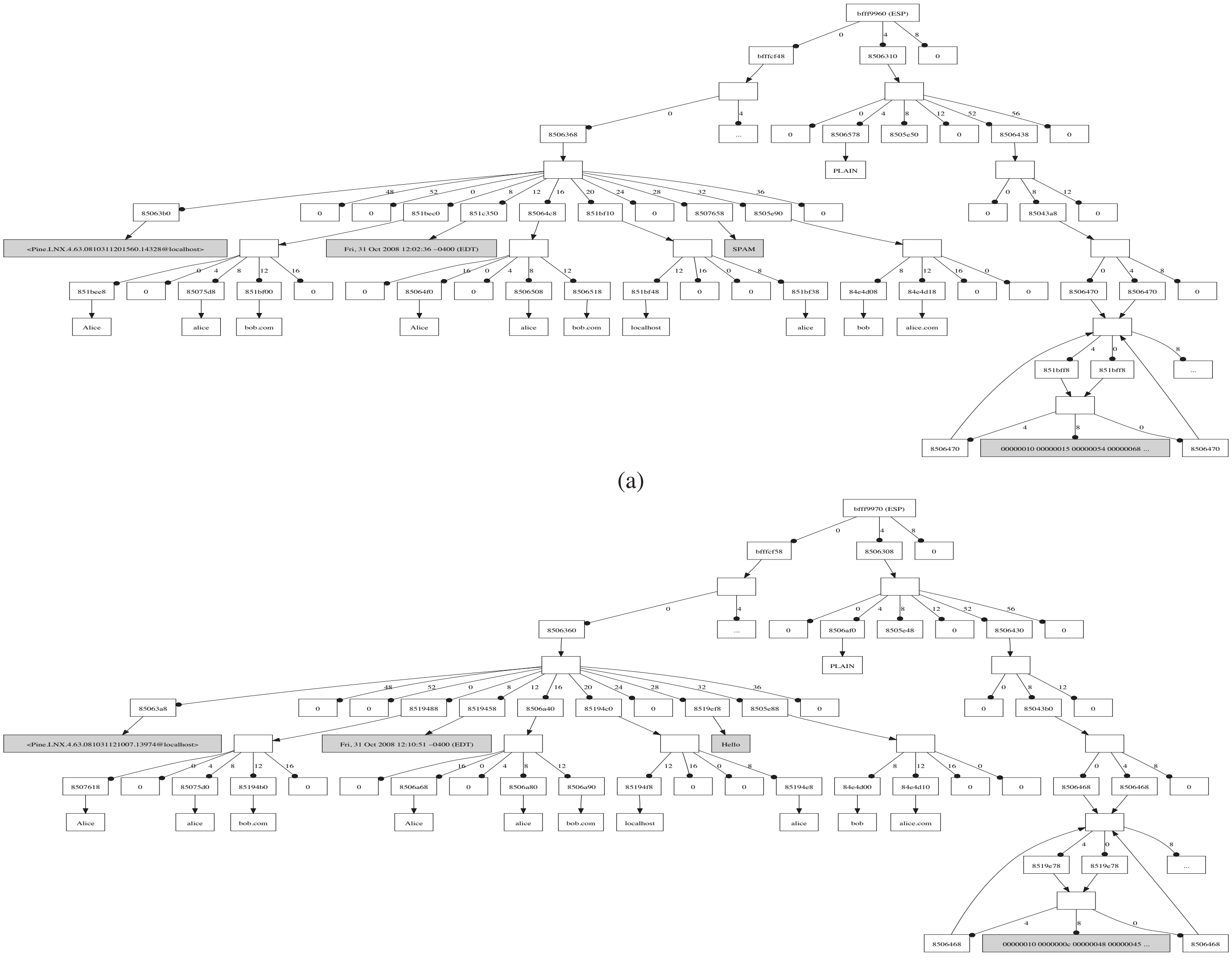
- *There is a field edge between nodes n and m, denoted as $n \multimap m$, if m is a field of n. The field name is annotated on the edge. If symbolic information is not available, the offset is annotated.*
- *There is a pointer edge between nodes n and m, denoted as $n \longrightarrow m$, if n stores a pointer that points to m.*

In our `pine` example, we acquire two executions by running `pine` twice, with the same configuration and the same sender and recipient addresses, but different subjects and email contents. We show these two test emails in Table 2: one is a spam email and the other is a regular one.

The two RGs at the invocation point of `call_mailer` are presented in Fig. 4. The root nodes represent the current stack frame (the roots for the global regions are irrelevant for our discussion and thus omitted). In Fig. 4(a), three fields have been reverse engineered with the byte offsets of 0, 4 and 8. The first two are pointers, the last one contains a value 0. The first pointer field `0xbfffcf58` points to a memory region that has two fields, and so on.

The two memory snapshots are aligned by aligning their RGs. Since RGs are graphs with labels, their alignment can be carried out by a simple labeled graph alignment algorithm. A memory difference is defined as a memory region that has a different value in its alignment in the other RG. Observe the two RGs in Fig. 4 are highly similar. The differences are highlighted in the figure. Note that pointer value differences are ignored to tolerate non-determinism in memory allocation. Two out of the four differences are for the subject and the content. The other two are for different time-stamps and book-keeping information. Note that the content is encoded, which justifies our approach of memory diff-ing because a simple scan over the memory would fail to find the content.

Besides identifying critical memory regions, another goal of RG is to provide reference paths to these regions. A reference path is a RG path that starts from a root and



(a)

(b)

Figure 4. RGs at the invocation of `call_mailer` for sending (a) a spam and (b) a regular email.

leads to the destination region. It indicates how to address the region at the current execution point. The software is vulnerable only if such paths can be reverse engineered. Then a ROC attack can be easily composed by mutating the values of these regions. In Fig. 4, the reference paths from the roots to the differences can be discovered from the RGs. For example, the reference paths to the subject and the content are *(*(*(`ESP`+0)+0)+28) and *(*(*(*(*(`ESP`+4)+52)+8) +0)+0)+8), respectively. Dictated by the definition of memory alignment, the paths to the corresponding memory regions (e.g., the paths to email subject) are identical in the two graphs. We point out that the normal execution can be mutated to the malicious one if the values in the shaded regions in (a) are copied over to the regions in (b) at the execution point where the snapshot is taken.

Reference Graph Construction. RGs play an important role in ROC vulnerability detection. On the surface, an RG is very similar to the object reference graph for garbage collection in object-oriented programs [8] or the memory graph [31] in C programs. The difference is in our context as we do not assume any data structure knowledge. Only based on the identifiable memory regions and size information, e.g., global variable region and size, stack frame address and size, heap chunk address and size, we build the corresponding RG rooted from the global variables and stack variables on the current frame. The details on how to build RGs are elided and can be found in our technical report [22].

4 ROC Attack/Trojan Composition

Given a grammar specification, our ROC vulnerability detector identifies feature functions and critical arguments with their reference paths. If both can be identified, the software is highly susceptible to ROC attacks. To confirm a ROC vulnerability, we further develop an attack composer

Macro/Method	Description
BEFORE(int `func`) {code}	insert the code block before `func`
AFTER(int `func`) {code}	insert the code block after `func`
ENTRY(int `func`) {code}	insert right inside `func`
void get(int* `field`)	retrieve the argument `field`
void set(int* `field`, void* `val`)	set the argument with `val`
void duplicate(int `func`)	duplicate the invocation of `func`

Table 3. ROC attack composition API.

that allows user to construct ROC attacks.

Recall that feature functions are those that emit the specified output and their invocations can be duplicated for subversion if needed as they do not have irreversible side effects. Furthermore, critical arguments of these functions and their reference paths also allow mutating the arguments. Therefore, we propose a programming interface that facilitates easy ROC attack composition. As shown in Table 3, the interface provides macros that allow inserting code before or after a function invocation, or right at the beginning of the invoked function. It also supports simple argument manipulation and function call duplication. A ROC attack can be written using a C-like language with the APIs. The following code snippet illustrates a ROC attack that redirects an email message.

```
BEFORE(call_mailer){
    set(&receiver, "ghost@somewhere.com");
    duplicate(call_mailer);}
```

The attack duplicates the `call_mailer` invocation and mutates the `receiver` of the email address before the duplicated call. The attack code is inserted before the original invocation to `call_mailer`. Note that our tool identifies the address for the given `call_mailer` function and the reference path for `receiver`. The result is that a copy of the email is sent to the malicious address before it is sent to the right receiver. The snippet will be translated into assembly code and then compiled to a piece of independent binary. The binary will then be patched to the original software. The patch contains three parts: an *entry patch* that precedes the duplicate and intercepts the control flow right before the original benign invocation; a *malicious logic* that implements the main body of the attack; and an *exit patch* that reverses the side effects. The malicious logic includes accessing and changing the critical argument denoted by the field name *receiver* and making a duplicated call. The field represents the argument that decides the output value parsed by the non-terminal *Receiver* in grammar $\mathcal{G}$, denoting the receiver's address. The patch is further weaved into the original binary. Details can be found in [22].

5 Evaluation

We have implemented the ROC vulnerability detector using Valgrind-3.2.3 [24]. We instrument a binary to (1) collect memory reads, writes, data dependencies, heap allocations, and de-allocations, along with the call stack contexts; (2) keep track of function live ranges, caller-callee relations; and (3) take snapshots of memory along with regular registers for reference graph construction at the selected function invocation points. Feature extraction, side effect analysis, and RG-based memory diff-ing are conducted off-line based on the trace file. The ROC attack composer is implemented independently. We have applied our framework to a number of real-world binaries. In the following, we present the results from our ROC vulnerability detector and attack composer.

Benchmark		Time	#Traced Threads	Log Size
Software Name	Size			
pine-4.63	6.3M	8m25s	1	6.4G
mailx-12.4	712K	5m48s	1	2.9G
mutella-0.4.5	843K	10m16s	9	8.2G
peercast-0.1217	58K	15m18s	5	3.5G
gift-0.11.8.1	321K	7m57s	1	2.2G
libGnutella.so.0.11	657K	12m36s	1	3.1G

Table 4. Cost of profiling for feature extraction.

5.1 Overall Result

In our experiments, we assume some high-level knowledge about a target binary's semantics such as the communication protocol used. In particular, our evaluation mainly involves two protocols, an email protocol (RFC-2822) and a P2P protocol (Gnutella-0.6). We aim to detect ROC vulnerabilities in various implementations of these protocols. We take 5 widely used software programs as benchmarks as shown in Tables 4 and 5. The "Size" column in Table 4 is the binary size. In the email implementations (`pine` and `mailx`), we aim to find the feature responsible for email sending so that we can use it to redirect email or send spam. In the P2P programs (`mutella`, `peercast`, and `gift`), we aim to implant malicious logic such as a C&C channel.

Table 4 shows the cost of profiling in the feature extraction phase. The profiling consists of one expensive instruction level profiling and 10 featherweight function level profiling. The instruction level profiling collects memory reads, writes and dependencies and produces large log files. It is to facilitate containing function identification. The function level profiling is to identify containing functions that are not dedicated to the feature, i.e., containing functions executed in runs that do not produce the specified output (or do not accept the specified input). The overall cost is presented in Table 4. The overall profiling time, the maximal number of traced threads for one run, and the total log size are shown in the 3^{rd}, 4^{th}, and 5^{th} columns, respectively. Note that `libGnutella` is a plug-in in `gift`. They are treated as two different benchmarks because we are interested in their different features, namely, the file index management feature in `gift` and the file transfer feature in `libGnutella`. The first instruction level profiling is the dominant factor in the cost. Currently, it collects traces for the entire execution which is sub-optimal. We will work on optimizing this component in the future.

Table 5 summarizes the input and outcome of the detector. The columns in `Prior Knowledge` presents the information provided by user: `Protocol` is the feature rep-

Benchmark	Prior Knowledge		Observed Feature Function		Max Length of Ref Path	#Identified Var	#Containing Functions	Side Effect Write		
	Protocol	#Var	Func Addr	Func Name				#G	#H	#F
pine-4.63	RFC-2822 Email Sending	4	0x081c613c	compose_mail	1	1	7	183	9	1
			0x081cbf67	pine_send	3	0	8	181	37	1
			0x081d5b6f	call_mailer	6	4	9	18	9	0
mailx-12.4	RFC-2822 Email Sending	4	0x08090f59	talk_smtp	3	3	10	3	2	0
			0x08092306	smtp_mta	3	3	9	9	1	0
			0x0808e864	start_mta	3	3	8	18	1	0
			0x0808e6a2	transfer	3	3	7	18	1	0
			0x0808ee02	mail1	3	3	6	70	1	2
mutella-0.4.5	Ping Send	1	0x080d0cc2	MGnuNode::SendPacket	5	1	15	1	1	0
			0x080d2eb8	MGnuNode::Send_Ping	4	1	14	1	1	0
	Ping Recv	1	0x080d64e2	MGnuNode::HandlePacket	5	1	8	-	-	-
			0x080d1b1c	MGnuNode::Receive_Ping	4	1	9	-	-	-
peercast-0.1217	Ping Send	1	0xb7eee13e	GnuStream::ping	1	1	9	0	6	0
			0xb7eedf5a	GnuStream::sendPacket	3	1	8	0	6	0
	Ping Recv	1	0xb7eef3b6	GnuStream::processPacket	6	1	8	-	-	-
gift-0.11.8.1	Index Management	0	0x08054923	share_update_index	5	0	16	-	-	-
			0x0805489e	update_index	5	0	17	-	-	-
libGnutella.so.0.11	Query Recv	1	0xb7dc522a	recv_packet	3	2	21	-	-	-
			0xb7d027fe	gt_msg_query	3	1	22	-	-	-
	Ping Recv	1	0xb7d01659	gt_msg_ping	4	1	22	-	-	-

Table 5. Summary of results from ROC vulnerability detector.

resented by the provided grammar; `#Var` shows the number of critical arguments, which correspond to some non-terminals in the grammar. The columns in `Observed Feature Functions` show the extracted feature functions. Note our techniques do not require any symbolic information, and we present function names mainly for readability. The next three columns show the maximal length of the reference paths of the critical arguments; the number of critical variables identified; and the number of containing functions. The side effect columns present the number of writes to global variables (`#G`), heap variables that are live at the end of the function (`#H`), and external files (`#F`). Note if the patch is not a function duplication, we do not collect the side effect data.

After the ROC vulnerabilities are identified, we use our attack composer to construct ROC trojans thus confirming the vulnerabilities. Except that `mailx` has an irreversible side effect, other binaries have been successfully exploited. Due to space limitation, we next present one representative case study on how we analyze the `mutella` binary, and we leave the details of other case studies in our technical report [22].

5.2 A Case Study

Malicious intent and desirable features: In this case, we are interested in stealthily introducing a covert Botnet command and control (C&C) mechanism to the `mutella` implementation. The idea is to reuse the Gnutella (the protocol used by `mutella`) internal management protocol so that network packets would look normal and the C&C overlay is completely invisible to the peers. In particular, from the Gnutella protocol specification [2], we know a "PING" packet is used to announce the presence of a node on the network; and other peers respond with a "PONG" packet to notify they are reachable. The "PING" message is also forwarded to other connected peers before reaching the maximum hops. We can encode various botnet commands by sending the identical "PING" packet in sequences of various length. Note that doing so is completely legal according to the protocol specification (as such behavior corresponds to a node trying to find its neighbors). The un-infected peers would work normally whereas only the infected peers (bots) would understand such encoding among themselves.

Reuse-able function identification: We provide the PING message grammar to the ROC vulnerability detector with the critical argument being GUID (the identification of a message). Note that we are interested in both PING message sending and receiving features. They are considered separate features as they are implemented by different sets of functions. For the PING send and PING receive features, two feature functions and the critical argument are identified, indicating that `mutella` is vulnerable. We select `Send_Ping` and `Receive_Ping` to compose the attack. Part of the attack code is presented as follows.

```
BEFORE(Send_Ping) {
    for(i=0;i<2;i++){//Command A
        duplicate(Send_Ping);
    }
}
ENTRY(Receive_Ping) {
    get(&GUID);
    if(two consecutive messages with identical GUID)
        do_command_A();
}
```

Attack logic composition: The patch duplicates the invocation of `Send_Ping` and wraps the duplication into a loop, with the number of iterations dependent on the specific C&C command. The second half of the attack code handles the receiving end of the "PING" messages by interpreting the command. It gets the argument `GUID` at the invocation to `Receive_ Ping`, decodes the command based on the number of consecutive messages with the same id, and takes the corresponding action. The `get` function concerns input instead of output. It is translated to a memory access following the reference path to the reverse engineered argument `GUID`, which is `*(ESP+0)` in this case. Moreover, since feature functions concerning input are not likely to get duplicated, our detector does not analyze their side effects, which explains the '-' symbols in the side effect columns in Table 5.

6 Discussion

Having demonstrated the feasibility of ROC attacks and their potential threats, we now discuss possible approaches to ROC attack detection and prevention.

Binary integrity check. The most intuitive way to detect ROC attacks is to hash all legal binaries (e.g., using Tripwire [20], or NSRL [3]) and periodically check their integrity. In practice, however, it is difficult to maintain up-to-date, globally consistent hash values, considering the frequent, automatic software patching and update, as well as the decentralized distribution of binaries and patches. Moreover, users may not always enforce timely binary integrity check. In fact, one purpose of this work is to promote such practice. This, in part, explains the prevalence of trojans and other drive-by downloads on today's Internet. Meanwhile, it is also impossible to hash all malware (including trojans) samples for their detection, due to the large amount and the dynamics of today's malware [12].

Control flow integrity check. A ROC attack does not violate control flow integrity except at the entry and exit points where the malicious patch gets the control. Therefore it may be possible to detect such violations by monitoring and profiling the binary's normal control flows and enforcing them at runtime. For example, we could use CFI [7] to enforce legal control flow transfers at those entry/exit points. One challenge would be that, since the CFI enforcement itself is *part of* the victim binary, the ROC attacker may bypass the CFI check as part of its side-effect elimination patch.

Host-based IDS. ROC attacks are carried out by duplicating existing, legal function invocations. As such, the attacks may be oblivious to many host-based intrusion detection systems (e.g., VtPath [16]). However, the timing/sequencing characteristics of the duplicated feature function invocations may provide a lead for their detection. Hence, detectors based on behavioral sequence analysis (e.g., [18]) may be able to detect ROC attacks.

Network-based IDS. ROC attacks are able to preserve the normal network behavior of the victim binary, as demonstrated by the `mutella` case study. As such, most network-based IDSes (e.g., PAYL [28]) would not pickup behavior abnormality. However, depending on the nature of a specific ROC trojan, it is possible that an NIDS using *content-based* signatures be able to detect its malicious traffic (e.g., spams). Such detection, unfortunately, cannot be generalized to all ROC trojans.

To prevent ROC attacks, one way is to break the software modularity, e.g., by transforming a program so that it contains very few function calls, which can no longer be singled out to perform a malicious action without side-effects. Another approach is to obfuscate the binaries so that it would be difficult to identify reuse-able functions. In fact, many malware programs in the wild adopt such strategy to avoid detection. We argue that legitimate programs may also benefit from obfuscation in preventing ROC attacks.

7 Related Work

Return-into-libc attack. The ROC attack is related to the return-into-libc attack [15, 23]. The return-into-libc attack requires prior knowledge about the implementation of the returned library functions and is defeat-able by randomization techniques [19]. On the other hand, the ROC attack uses dynamic program analysis techniques to infer the reuse-ability of application level functions. More importantly, the control flow deviation caused by return-into-libc attacks is fairly obvious and easily detectable; whereas ROC attacks by design try to mimic the control flow of the victim program and reverse any side-effects.

Return-oriented programming. Shacham et al. recently proposed a return-oriented programming paradigm [27, 10], which reuses existing instruction sequences in large code segments (e.g., library) to compose malicious logics. This paradigm enables reuse of very basic functionalities at the granularity of short instruction sequences; whereas ROC attacks reuse high-level functional features of software at the (much coarser) granularity of modular functions.

Feature extraction. Prior work exists in feature extractions from binaries. Wong et. al. proposed an execution slice-based technique to identify the basic blocks which are used to implement a program feature [29]. Greevy et. al. proposed a compact feature-driven approach based on dynamic analysis to characterize features and computational units of an application [17]. Pattabiraman et. al. presented using symoblic execution to enumerate all possible application level "insider" attacks [26].

More recently, Caballero et al. [11] independently proposed a binary code extraction technique, BCR, by combining dynamic and static analysis, to extract the malware encryption and decryption functions and reuse them in a network proxy (to decrypt the encrypted traffic). They mainly focus on how to extract the transformation function in which the entry point needs to be given, inside the binary, for the purpose of malware analysis. In addition, they reuse the transformation code in a *different* program (i.e., the malware analysis program); whereas we reuse the code within the *same* binary, with additional requirements (e.g., side-effect minimization and reversal). The Inspector gadget [14] is another independent effort that focuses on extracting and reusing features inside malware programs.

Memory Graph. Our reference graph (RG) concept is similar to the object reference graph for garbage collection in object-oriented programs [8] and the memory graph [31] in C programs. An object reference graph has objects as its nodes connected through their field edges. It mainly focuses on the management of dynamically allocated memory. A memory graph has dynamic data structures as its nodes and "points-to" relations as its edges. Memory graphs require prior knowledge about data structure definitions [31]; whereas our technique for ROC attack construction assumes only binaries. In addition, the requirement of RG is less stringent, meaning that an RG is valid as long as it provides valid reference paths to specific memory regions without requiring the nodes and edges to precisely follow the actual data structure definition. The garbage collector by Boehm [9] also traverses memory to find reachable regions without demanding symbolic information. It does not explicitly build the reference graph and its traversal is coarse-grained, without capturing field information.

8 Conclusion

The ROC attack/trojan poses a new threat, virtually transforming a legal binary into a stealthy, malicious one. The neutral functional features in a legal binary are potential targets of ROC attacks. ROC trojans are heavily dependent on the semantics of their victim binary programs and there exists no generic content or behavior "signature" across all ROC attacks. To defend against ROC attacks, we present an integrated framework for the detection of ROC vulnerabilities in a binary and for the construction of concrete ROC trojans. Our experiments with a number of real-world software binaries indicate that the ROC attacks are real and ROC vulnerabilities can be detected and confirmed in a systematic fashion.

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References

[1] Bitdefender malware and spam survey. *http://news.bitdefender.com/NW1094-en–BitDefender-Malware-and-Spam-Survey-finds-E-Threats-Adapting-to-Online-Behavioral-Trends.html*.

[2] Gnutella protocol spec. *http://wiki.limewire.org/index.php?title=GDF*.

[3] National Software Reference Library. *http://www.nsrl.nist.gov/*.

[4] Most abused infection vector. *http://blog.trendmicro.com/most-abused-infection-vector/*.

[5] Virus collection (vx heavens). *http://vx.netlux.org/vl.php, visited in Nov. 2009*.

[6] Parasitic malware: The resurgence of an old threat. *Network Security*, 2008(3):15 – 18, 2008.

[7] M. Abadi, M. Budiu, Úlfar Erlingsson, and J. Ligatti. Control-flow integrity. In *ACM CCS'05*, 2005.

[8] O. Agesen, D. Detlefs, and J. E. Moss. Garbage collection and local variable type-precision and liveness in java virtual machines. *SIGPLAN Not.*, 33(5):269–279, 1998.

[9] H.-J. Boehm. Space efficient conservative garbage collection. In *ACM PLDI'93*, 1993.

[10] E. Buchanan, R. Roemer, H. Shacham, and S. Savage. When good instructions go bad: Generalizing return-oriented programming to RISC. In *ACM CCS'08*, 2008.

[11] J. Caballero, N. M. Johnson, S. McCamant, and D. Song. Binary code extraction and interface identification for security applications. In *ISOC NDSS'10*, 2010.

[12] J. Canto, M. Dacier, E. Kirda, and C. Leita. Large scale malware collection : lessons learned. In *IEEE SRDS'08*, 2008.

[13] J. Chow, B. Pfaff, T. Garfinkel, K. Christopher, and M. Rosenblum. Understanding data lifetime via whole system simulation. In *13th USENIX Security Symposium*, 2004.

[14] C. Kolbitsch, T. Holz, C. Kruegel and E. Kirda. Inspector gadget: Automated extraction of proprietary gadgets from malware binaries. In *IEEE Symposium on Security and Privacy*, 2010.

[15] S. Designer. "return-to-libc" attack. *Bugtraq*, August 1997.

[16] H. H. Feng, O. M. Kolesnikov, P. Fogla, W. Lee, and W. Gong. Anomaly detection using call stack information. In *IEEE Symposium on Security and Privacy*, 2003.

[17] O. Greevy and S. Ducasse. Correlating features and code using a compact two-sided trace analysis approach. In *European Conference on Software Maintenance and Reengineering*, 2005.

[18] S. A. Hofmeyr, S. Forrest, and A. Somayaji. Intrusion detection using sequences of system calls. *J. Computer Security*, 6(3):151–180, 1998.

[19] A. D. Keromytis. Randomized instruction sets and runtime environments past research and future directions. *IEEE Security and Privacy*, 7(1):18–25, 2009.

[20] G. H. Kim and E. H. Spafford. The design and implementation of tripwire: a file system integrity checker. In *ACM CCS'94*, 1994.

[21] B. Korel and J. Laski. Dynamic program slicing. *Information Processing Letters*, 29(3):155–163, 1988.

[22] Z. Lin, X. Zhang, and D. Xu. Reuse-Oriented Camouflaging Attack: Vulnerability Detection and Attack Construction. Technical report, CERIAS TR 2009-29, Purdue University, 2009.

[23] Nergal. The advanced return-into-lib(c) exploits: Pax case study. *Phrack*, 10(58), 2001.

[24] N. Nethercote and J. Seward. Valgrind: A framework for heavyweight dynamic binary instrumentation. In *ACM PLDI'07*, 2007.

[25] J. Newsome and D. Song. Dynamic taint analysis for automatic detection, analysis, and signature generation of exploits on commodity software. In *ISOC NDSS'05*, 2005.

[26] K. Pattabiraman, N. Nakka, Z. Kalbarczyk, and R. Iyer. Discovering Application-Level Insider Attacks Using Symbolic Execution. In *Proc. of the 24th IFIP SEC*, 2009

[27] H. Shacham. The geometry of innocent flesh on the bone: return-into-libc without function calls. In *ACM CCS'07*, 2007.

[28] K. Wang and S. J. Stolfo. Anomalous payload-based network intrusion detection. In *Recent Advances in Intrusion Detection*, 2004.

[29] W. E. Wong, S. S. Gokhale, and J. R. Horgan. Quantifying the closeness between program components and features. *J. Syst. Softw.*, 54(2):87–98, 2000.

[30] H. Yin, D. Song, E. Manuel, C. Kruegel, and E. Kirda. Panorama: Capturing system-wide information flow for malware detection and analysis. In *ACM CCS'07*, 2007.

[31] T. Zimmermann and A. Zeller. Visualizing memory graphs. In *Revised Lectures on Software Visualization, International Seminar*, 2002.

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