ROPMate: Visually Assisting the Creation of ROP-based Exploits

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Abstract

Exploits based on ROP (Return-Oriented Programming) are increasingly present in advanced attack scenarios. Testing systems for ROP-based attacks can be valuable for improving the security and reliability of software. In this paper, we propose ROPMate, the first Visual Analytics system specifically designed to assist human red team ROP exploit builders. In contrast, previous ROP tools typically require users to inspect a puzzle of hundreds or thousands of lines of textual information, making it a daunting task. ROPMate presents builders with a clear interface of well-defined and semantically meaningful gadgets, i.e., fragments of code already present in the binary application that can be chained to form fully-functional exploits. The system supports incrementally building exploits by suggesting gadget candidates filtered according to constraints on preserved registers and accessed memory. Several visual aids are offered to identify suitable gadgets and assemble them into semantically correct chains. We report on a preliminary user study that shows how ROPMate can assist users in building ROP chains.

Keywords: Malware Analysis, Return-Oriented Programming, Code Reuse, ROP Exploits, Visual Analytics.

1 Introduction

Code reuse techniques have become prevalent attack vectors against memory vulnerabilities, effectively circumventing traditional system defenses against code injection [13]. Among them, return-oriented programming (ROP) has received considerable attention as it allows an attacker to induce arbitrary behavior in a vulnerable program through a carefully crafted chain of redirections in the program memory, without actually injecting any additional code [19].

A typical attack scenario is based on a controlled stack frame where the return address can be overwritten by means of a buffer overflow. A ROP attack uses short instruction sequences (called *gadgets*) that are already present in the vulnerable application, as their combination allows for arbitrary computations. Each gadget usually takes the form of a few instructions, with the last one being a return. This allows the attacker to place on the stack a sequence, called *ROP chain*, made of gadget addresses and immediate operands, that will be executed as a whole thanks to the role of the `ret` assembly instruction in transferring control between consecutive gadgets.

Building a chain of gadgets is a hard task and this paper aims at progressing in this field by presenting a Visual Analytics system that allows for complementing automatic tools with human intervention – a paradigm successfully explored in other security research [5, 20]. The system provides visual cues that help a human ROP chain builder, making the creation of part or the totality of the chain easier.

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Indeed, while existing ROP tools [1, 2] do a very good job in finding useful gadgets, they provide limited support when building complex chains. Recently, solutions have been proposed to build chain portions for carrying out specific tasks only [10]. Overall, no automatic tool currently provides a general solution for dealing with complex dependencies and subtle side effects that often emerge when crafting chains for real-world programs. In this scenario, building ROP exploits remains predominantly a manual task.

The contribution of the paper aims at attacking this problem: it introduces ROPMate, a Visual Analytics solution supporting the manual construction of the chain for the exploit. The analytical part of the system analyzes the source of the gadgets, producing a list of semantically meaningful gadgets, with the obvious advantage that only gadgets that have a clear effect are maintained and presented to the user. The visual component shows the list of all meaningful gadgets, divided by class and by implemented operation; suitable properties are visually encoded and the user can further filter the list according to her need. Filtering may involve searching for gadgets that implement a particular operation, but, for example, do not modify some registers that have already been set, or access the memory only via some controlled registers, etc.

A preliminary formative user study allowed us to get pros and cons of the proposed approach and led to the development of a revised version of the system.

Summarizing, the contributions of the paper are the following:

- it introduces a novel Visual Analytics environment targeted at exploring and chaining gadgets to produce ROP exploits;
- it explores several analytical and visual solutions that support the user's task, presenting the most relevant gadgets and allowing for considering alternative solutions, e.g., providing the user with the information of existing gadgets similar to the one s/he is exploring;
- it provides a first feedback about the proposed system, collecting opinions from expert users and analyzing system usage traces to detect similar patterns and improve the system.

The paper is organized as follows: Section 2 presents the scenario in which the system has been developed; Section 3 discusses some related proposals; Section 4 presents the proposed Visual Analytics solution; Section 5 presents a case study; Section 6 presents a preliminary user study; finally, Section 7 draws some conclusions and presents an outlook for future work.

2 Application Domain

Programs written in type-unsafe languages such as C and C++ are vulnerable to attacks where an adversary corrupts the memory to have execution redirected to an arbitrary code sequence. Buffer overflows are the most frequent form of memory corruptions, with a program input being copied to a buffer without proper bounds checking. In particular, stack-allocated buffers have been historically used by attackers to inject their own code along with legit input data and eventually take control of a program.

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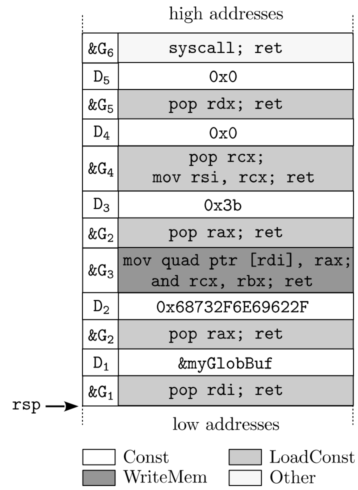
Table 1: Gadget categorization used in ROPMATE

CLASS	DESCRIPTION	EXAMPLE	
		OPERATION	GADGET INSTANCE
LoadConst	Load constant value into a register	`rax = 10`	`pop rax; ret`
ClearReg	Set to zero a register	`rax = 0`	`xor rax, rax; ret`
MovReg	Copy value from a register to a register	`rax = rcx`	`mov rax, rcx; ret`
UnOp	Unary arithmetic/logical oper. over a register	`rax += 1`	`inc rax; ret`
BinOp	Binary arithmetic/logical oper. over registers	`rax += rbx`	`add rax, rbx; ret`
ReadMem	Read value from memory	`rax = [rcx + 8]`	`mov rax, qword ptr [rcx + 8]; ret`
WriteMem	Write value into memory	`[rcx + 8] = rax`	`mov qword ptr [rcx + 8], rax; ret`
ReadMemOp	Binary operation with memory input	`rax += [rcx + 8]`	`add rax, qword ptr [rcx + 8]; ret`
WriteMemOp	Binary operation with memory output	`[rcx + 16] += rax`	`add qword ptr [rcx + 0x10], rax; ret`
StackPtrOp	Alter stack pointer value	`esp += 8`	`add esp, 8; ret`
Other	Any other operation	`syscall`	`syscall; ret`

```
mov rdi, offset myGlobBuf # G1+D1
mov rbx, 0x68732F6E69622F # G2+D2
mov qword ptr [rdi], rbx  # G3
mov rax, 0x3b             # G2+D3
mov rsi, 0x0              # G4+D4
mov rdx, 0x0              # G5+D5
syscall                   # G6
```




```
rop = ''
rop += p64(addr_G1)
rop += p64(myGlobBuf) # D1
rop += p64(addr_G2)
rop += '/bin/sh\x00'  # D2
rop += p64(addr_G3)
rop += p64(addr_G2)
rop += p64(0x3b)      # D3
rop += p64(addr_G4)
rop += p64(0x0)       # D4
rop += p64(addr_G5)
rop += p64(0x0)       # D5
rop += p64(addr_G6)
```

Figure 1: Traditional shellcode sequence (left), ROP counterpart (center), and Python script that generates the binary representation of the ROP chain (right) for executing system call `execve("/bin/sh", NULL, NULL)`. Function `p64` from the `pwntools` exploitation library is used to encode 64-bit representations. Immediate `0x68732F6E69622F` is the Little-Endian encoding of the NULL-terminated ASCII representation for `"/bin/sh"`. Addresses of gadgets G_i and immediate operands D_j are used to implement basic operations of the original shellcode. For the sake of readability, in the graphical representation of the chain we report the actual instructions inside each gadget instead of its address.

Once operating systems designers started incorporating defenses such as Data Execution Prevention (DEP), which hinders code injection by denying code execution from writable regions, attackers devised more subtle and powerful exploitation techniques commonly known as *code reuse attacks*. Such attacks chain together existing code fragments from the vulnerable application, granting an attacker the same expressive power of a custom injected sequence[1].

Return-oriented programming (ROP) is the most well-known form of code reuse, and takes its name from the `ret` assembly instruction that is used to chain together existing code fragments (called *gadgets*) of the application. `ret` is commonly used in function epilogues to update the instruction pointer with a value previously stored on the stack to resume execution in the caller function.

Gadgets can be found in libraries, and sometimes within the program itself, using tools that implement variants of the Galileo discovery algorithm [19] such as ROPgadget [1] or ropper [2]. Depending on the size of analyzed code and the maximum length, the number of found gadgets can range from thousands for middle-sized programs, to tens of thousands for large libraries and programs [9]. Gadgets are then analyzed and classified according to the functionalities they provide: in Table 1 we report a possible categorization that we use in the gadget classifier analytical component of ROPMATE.

Example. In Figure 1 we present a simple exploit that opens a shell on the machine with the same privileges of the vulnerable application; such an exploit is commonly referred to as *shellcode*. Before techniques such as DEP were adopted by operating systems, a shellcode consisted of assembly instructions to be injected in the program, as in the left portion of the figure. In particular, in this example a `"/bin/sh"` string is assembled in CPU register `rbx`, and then copied to a writable memory area whose address is specified in register `rdi`. The shellcode then prepares the arguments for the Linux `execve` system call used to spawn a shell: on a x86-64 architecture, ordinal `0x3b` for the call is put in register `rax`, the address of the string in register `rdi`, and the remaining two arguments – both set to `NULL` – in `rsi` and `rdx`, respectively. Finally, instruction `syscall` is used to trigger the system call.

An equivalent ROP chain for the shellcode is shown in the middle part of Figure 1. We assume that an attacker placed the chain on the stack so that the stack pointer `rsp` points to the beginning of the chain when the vulnerable program executes some `ret` instruction. This instruction updates the instruction pointer `rip` with the value currently written on the top of the stack, then adjusts the stack pointer before execution continues from the new address in `rip`. As the stack grows from high to low addresses, `rsp` is moved to a higher address, i.e., it is incremented by 8 on a 64-bit machine.

In our example, `ret` loads the address of gadget G_1 into the instruction pointer, and the updated stack pointer now points to D_1, which contains the address `&myGlobBuf` of the buffer where we will

[1]Code reuse attack techniques are usually Turing-complete [18].

put the "/bin/sh" string. As the code of gadget G_1 is executed, we meet one peculiarity of ROP code: constants are usually loaded to registers by means of `pop` instructions, which read a value from the top of the stack, write it to the desired register, and then increment `rsp`. When the next instruction in G_1 is executed, which is a `ret`, the top of the stack contains the address of gadget G_2: we can now see how the `ret` instruction orchestrates the control flow in a ROP chain, by loading the address of the subsequent gadget in the instruction pointer and moving the stack pointer up the chain before executing the gadget. Such process is iterated over the 7 gadgets that constitute the chain, eventually invoking `execve` as in the original shellcode.

Challenges. Building a ROP chain is not a trivial task. While for a traditional shellcode an attacker can choose from the entire CPU instruction set whichever instruction s/he need to implement the desired semantics, a ROP chain builder is strongly limited by the gadgets that are found during the discovery phase [18]. In particular, when looking for an instruction implementing a particular operation the following problems may arise:

1. *No available gadget contains it.* For instance, the chain builder is looking for a gadget that loads a constant value into a specific register, say `rbx`, but no suitable one is found. In the chain of Figure 1, we had to resort to a gadget G_2 that loads a constant to a different register, specifically `rax`. Another possibility is to use multiple gadgets to realize the intended operation: this happens for instance quite frequently for some arithmetic operations for which gadgets are notoriously rare [19].
2. *A gadget is available, but comes with side effects.* This is the case of gadgets with more than one instruction before the ending `ret`: for instance, gadget G_3 of Figure 1 not only writes the content of `rax` to memory, but also performs a bitwise AND operation, altering the contents of register `rcx`. In our example we do not use `rcx` to hold any relevant data for later use, thus this side effect is harmless. However, in general side effects might *clobber* (i.e., overwrite) registers holding useful data, or perform unwanted memory operations that may make the program crash or ruin the chain.
3. *A gadget is available, but is problematic for subsequent operations.* This case is more subtle, as an attacker has not only to consider the current operation, but also subsequent ones that will use its results. This happens for instance when some data is written to some register *r*, gadgets for subsequent operations can only read from different registers, and no other gadget can be used to move data across *r* and any such register.

In the light of these problems, a ROP chain builder is presented with a large amount of information originating in: (i) having many gadgets that differ only for subtle side effects, (ii) complex dependencies that may arise as the chain grows, and (iii) limitations on choosing a gadget on the basis of the registers that should not be clobbered at a given point in the chain.

While automatic construction of ROP exploits has been addressed in previous works, such as the seminal Q paper [18], most available tools do not work properly in realistic scenarios. Due to the lack of a publicly available working ROP compiler that meets the needs of real-world attackers, building ROP chains remains predominantly a manual task [10].

Applications. In recent years a remarkable number of academic works and security reports have highlighted the power of code reuse attacks for carrying out complex exploitations on mainstream software. A common belief is that most ROP exploits observed in the wild have been written manually by very experienced attackers which, either for demonstration purposes or motivated by criminal reasons, are willing to devote a significant effort to building a chain.

From a software house perspective, when a number of memory bugs are discovered in the development of its products, it is important to quickly assess whether such bugs are vulnerabilities exploitable by an attacker, and how dangerous the possible consequences are. For this reason, a *red team* made of ethical hackers – either internal or hired in the market – can evaluate the feasibility of ROP-based attacks, and to which extent such attacks can cause harm to the system. For instance, an attack might take place only under unrealistic operating conditions, or the attacker has limited freedom in carrying out certain tasks. It is important to consider that producing a fix for a vulnerability and validating it before releasing it publicly might take considerable time. Also, in some cases previous ROP exploits are adapted when variants of the original vulnerability surface later on, such as in the case of the EPS component of Microsoft Office[2]. Similar considerations might also apply for instance to companies that have to employ possibly buggy third-party components in, e.g., mission-critical systems.

3 Related Work

In cybersecurity, software vulnerabilities are considered one of the main attack vectors: the Visualization field presents several proposals coping with software analysis, ranging from code and structure analysis [11,24] to reverse engineering [8], malware analysis [12,16], and support for red team activities [25]. Given the specific nature of the ROP chain building activity, to the best of our knowledge no Visual Analytics solution has been previously proposed. In the remainder of this section, we discuss aspects of the ROP literature that are most related to our ideas.

ROP Defenses. In the arms race between OS designers and exploit writers, a number of defenses [22] have been proposed during the last decade to counter code reuse attacks. Address Space Layout Randomization (ASLR) [15] is one of the first defenses integrated into modern operating systems: by randomly arranging the address space positions of key areas of a process, ASLR makes hard for an attacker to identify gadget addresses. However, ASLR does not typically randomize the base address of the main executable, leaving a fruitful source for gadgets. Additionally, ASLR is often defeated by leveraging a vulnerability that leaks the base address of a library.

Several other defenses can be deployed to limit ROP attacks. For instance, G-Free [14] rewrites the application code to reduce the number of available gadgets, while TypeArmor [23] makes gadgets for function calls unusable outside legitimate control flows. The main drawback of sophisticated ROP defenses [22] is that they either come with non-negligible overheads or require heavily customized compilation toolchains, making them less suitable for production environments. With respect to ROP mitigations shipped with the latest releases of Microsoft Windows [3], a recent work [7] shows how these countermeasures can be bypassed. The work also discusses how to find find realistic expressive gadget sets even in the presence of advanced ROP defenses.

Automatic ROP Chain Builders. One missing element in the research landscape is a ROP chain building tool that meets the needs of real-world attackers, for which building a chain remains mainly a manual task [10]. Conversely, recent years have witnessed an increase in the complexity of ROP chains, which moved from being short sequences aiming at bypassing DEP to enable code injection, to very complex behaviors encoded entirely in ROP [13]. Gadget finders, such as ROPgadget [1] and ropper [2], provide very limited support to a user when building complex chains. While the most sophisticated tools can attempt to generate chains for a few predefined tasks, such as making the stack executable, they lack flexibility to support custom actions in an attack, and mostly importantly a robust methodology for dealing with gadget dependencies and subtle side effects automatically. As a consequence, they often fail and generate only partial chains that an attacker must complete manually, although in some cases such chains turn out to be a dead end.

[2] `https://www.fireeye.com/blog/threat-research/2017/05/eps-processing-zero-days.html`.

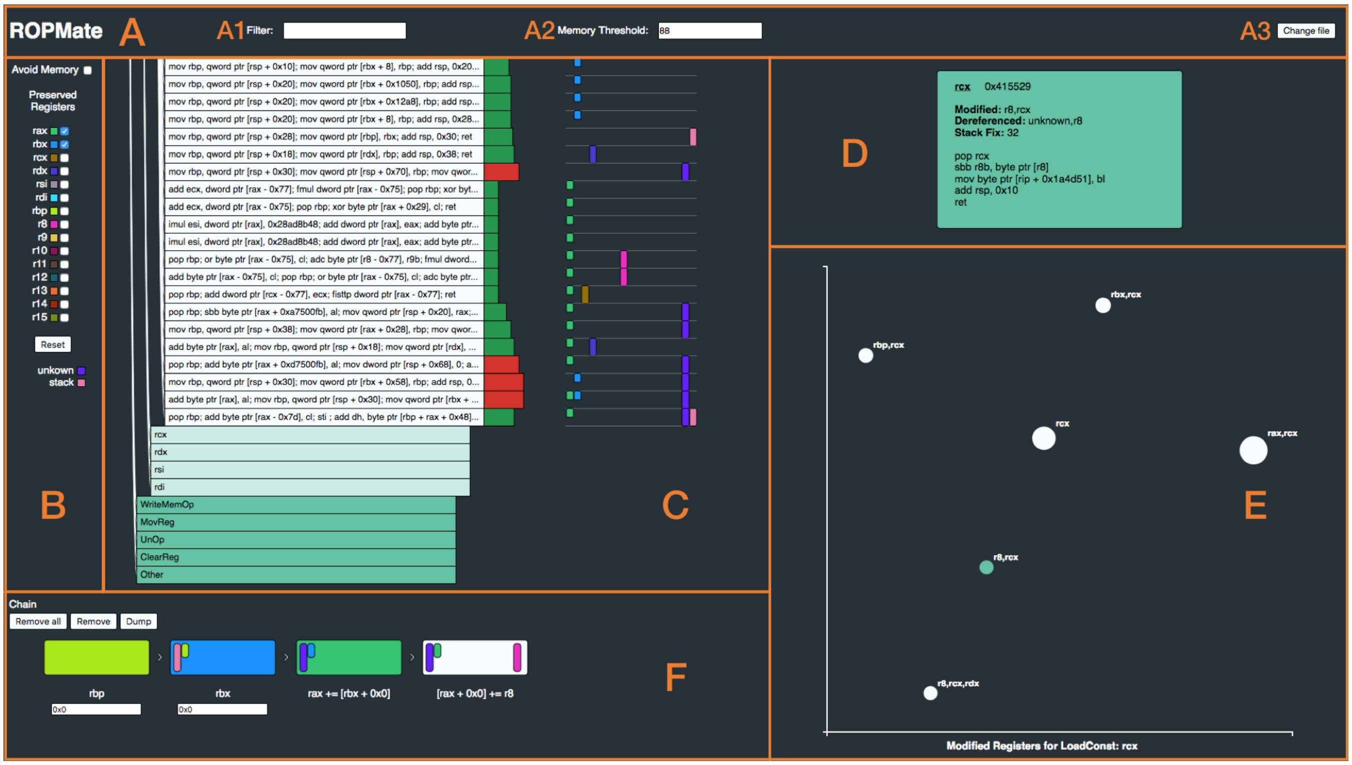


Figure 2: Overview of the ROPMATE visual component. **(A)** The top bar is divided in three parts, from left to right: **(A1)** the *Filter Bar* allows explicitly filtering the available gadgets by entering a search text; **(A2)** through the *Memory Threshold* it is possible to set a limit to the memory usage of gadgets; **(A3)** through this button it is possible to load the binary from which to extract the gadgets. **(B)** The *Registers Pane* lists all the registers and allows defining a filter on gadgets based on the preservation of certain registers; **(C)** the *Tree Pane* shows all the available gadgets organized in a three-level taxonomy; **(D)** the *Analysis Pane* shows the details of a chosen gadget, while **(E)** the *Similarity Pane* shows all the gadgets that execute the same operation using MDS. Finally, **(F)** the *Chain Pane* shows the current state of the built chain.

4 THE VISUAL ANALYTICS SOLUTION

The proposed solution aims at supporting the user in the whole process from the gadgets extraction to the ROP chain deployment. This section introduces this process, then describes the analytical and visual components that support it.

As first step, the program under inspection is parsed by the analytical component that extracts the set of available gadgets; each gadget is analyzed to identify its semantics and how it interacts with memory and registers. The subset of semantically meaningful gadgets is then loaded in the visual component and the user can start her analysis. In order to build the chain, the user has to iteratively repeat the following steps:

- S/he selects an operation to add to the chain and chooses a gadget with that semantics based on memory and registers constraints (see also Table 1);
- S/he analyzes more deeply the chosen gadget and adds it to the chain if it is appropriate or looks for similar gadgets otherwise;
- When a gadget is added to the chain, the user checks the chain behavior and optionally modifies it by reordering or deleting its gadgets.

When the chain is complete, s/he can export it to a Python script for its binary encoding, a step that is common in the ROP practice.

4.1 The Analytical component

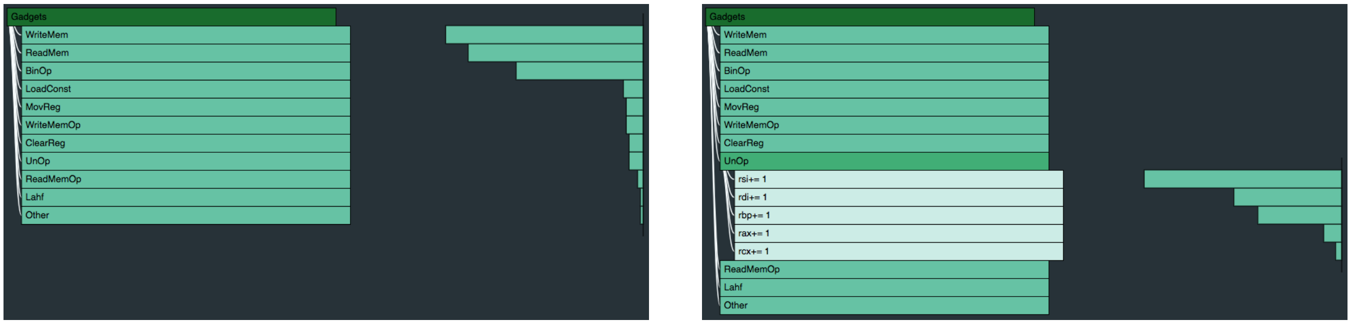
ROPMATE relies on different analytics, used in all the steps of the process, from the preprocessing step in which gadgets are characterized, to the management of the developed chain.

Gadgets Semantics: Classification and Filtering. During the preprocessing step, the analytical component analyzes the available gadgets extracted from the program and identifies their semantics using a classification algorithm based on symbolic execution [6]. It groups gadgets that execute the same *operation* (excluding useless gadgets) and that differ from each other in terms of memory and registers usage. The identified operations are further grouped in *classes* (see Table 1), thus creating a three-level taxonomy that makes easier to navigate through the different gadgets. The taxonomy allows the user to quickly identify a subset of suitable gadgets; however selecting the right gadget(s) among them require to take into account side effects like the clobbering of registers or unwanted memory operations. For this reason, each gadget representation is enriched with information regarding the reading, modification, or dereferencing of registers and memory operations. This information will be then conveyed through visual means to the user during the chain building process and can be used as further filter mechanisms.

Gadgets Similarity. Once a subset of gadgets that execute the same operation is identified, ROPMATE is able to compute a dissimilarity function among them in order to facilitate their exploration. Given a gadget G_i, it analyzes its semantics and builds the set S_i containing G_i and all the gadgets that execute the same operation. S_i is then partitioned in $P_i = \{Q_0, \dots, Q_n\}$ such that each subset Q_h contains all the gadgets that modify the same set of registers. For every pair $(Q_j, Q_k) \in P_i \times P_i$, the dissimilarity function $d(Q_j, Q_k)$ is computed as follows:

$$d(Q_j, Q_k) = |(R_j \cup R_k) - (R_j \cap R_k)|$$

with R_h being the set of registers modified by the gadgets of set Q_h,



(a) Classes

(b) Semantics

Figure 3: Details of the *Tree Pane* showing the first two levels of the taxonomy of gadgets: (a) the first level of the tree shows the list of 11 classes available for the binary and a histogram suggesting the number of operations for each class, (b) the second level of the tree shows the list of 5 operations available for the `UnOp` class and a histogram to convey information regarding the number of gadgets for each such operation.

and the relative dissimilarity matrix is built. That allows for quickly locating substitutes of G_i when, for any reasons, G_i cannot be used.

4.2 The Visual component

The first step while using ROPMATE is to load the program under examination (see Figure 2.A3); after that it is parsed by the analytical component that extracts and characterize gadgets as discussed in Section 4.1. Once the list of gadgets is extracted from the program, the user can start to build the ROP chain.

The *Tree Pane* (see Figure 2.C) shows the taxonomy of gadgets, grouped by operations and classes. The taxonomy is represented as a tree allowing to quickly locate suitable gadgets based on the desired operation by descending the tree. The first level of the tree shows the classes (see Figure 3a); a histogram aligned to the list of classes suggests the number of available operations for each class, with the width of the bars proportional to this number. Clicking on a class reveals the list of its operations (see Figure 3b). A second histogram is aligned to the list of operations; the width of the bars is now proportional to the number of available gadgets.

Once the desired operation is identified, the list of corresponding gadgets, partially ordered by ascending complexity (modeled as a heuristic of: number of dereferenced registers, number of modified registers, and stack pointer displacement, in this order) is available by clicking on it (see Figure 4). A gadget is identified by its assembly code and its representation is enriched by means of two visual elements. Each gadget has an associated *memory requirement bar* on its right; the width of the bar represents the space in the stack required by the gadget to work properly (i.e., to execute its instructions and being able to transfer execution to the next gadget), according to a logarithmic scale that allows for perceiving the differences among small values. The color of the bar encodes the stack occupation with respect to a memory threshold. A green color indicates that the size does not exceed the threshold, while a red color indicates that it does. The memory threshold has a predefined value but at any time the user can change this value according to her needs (see Figure 2.A2).

The second visual mean is the *dereferenced registers matrix*, aligned to the right of the gadgets and showing the registers used to access the memory; each column represents a register and the rows are aligned with the gadgets. Each entry of the matrix is filled by a rectangle if the gadget dereferences the register (suggesting that the register has to be properly set to safely use it to access the memory). The rectangle has a full height if the condition is not currently satisfied by the chain and it has half height otherwise; this visual encoding has been chosen to prioritize the identification of dependencies to resolve in case of gadget selection. Each rectangle has a color associated to the register, but the possibly high number of registers in 64-bit code led us to use this matrix representation instead of the listing of the registers for each gadget to take advantage of the horizontal positioning and make usage patterns evident.

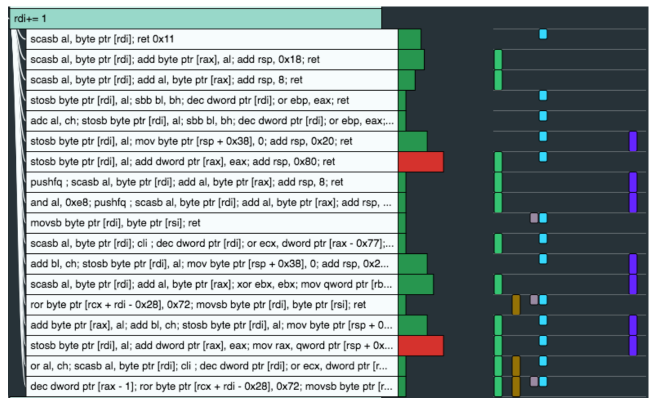


Figure 4: Details of the 18 available gadgets for the `rdi+=1` operation of Figure 3b. Gadgets are identified by their assembly code; the width of the *memory requirement bars*, attached to the right, is proportional to the binary logarithm of the required memory occupation (the red color of 2 boxes means that the requirement of the gadgets exceeds the memory threshold); the aligned *dereferenced registers matrix* shows which registers are dereferenced by each gadget, the entries are rectangles with full height if the dependency is not satisfied (e.g., `rax` register encoded in green), and have half height otherwise (e.g., `rsi` and `rdi` registers encoded in gray and light blue.)

The *Registers Pane* (see Figure 2.B) allows for further refining the search space in order to face the possible side effects: the user is able to select which registers should be preserved, for example to safely choose gadgets without clobbering registers already set in the chain. The pane contains all the registers, identifiable by their name and color and a checkbox that, when is checked, filters from the *Tree Pane* all the gadgets that modify the register. The user has also the possibility to display only gadgets that do not access memory to be able to choose simpler gadgets first, by checking the *Avoid Memory* check-box. Furthermore, through the *Filter Bar* (see Figure 2.A1), the user is allowed to explicitly define the filter by entering a search text: e.g., "`rdi`" filters gadgets using that register. S/he is able to select all and only the gadgets that execute a specific operation, that explicitly set up a certain register, or that use it to access memory.

Once the user selects a gadget, additional information is displayed in the *Analysis Pane* (see Figure 2.D). The box shows the operation carried out by the gadget, its assembly code, its memory address,

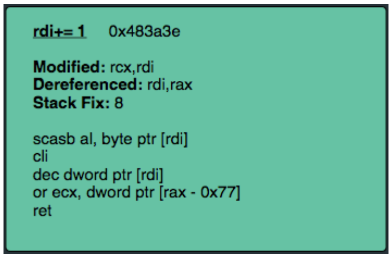


Figure 5: The box in the *Analysis Pane* provides details about one of the gadgets available for the `rdi+=1` operation: the gadget modifies the `rcx` and `rdi` registers, dereferences `rdi` and `rax`, and needs 8 bytes in memory to work properly; furthermore, its assembly code is detailed in the bottom of the box. By clicking on the box, the gadget will be added to the chain.

the registers that it modifies and the ones that it dereferences; an example is provided in Figure 5. By clicking on the box, the gadget is added to the chain.

While analyzing a gadget, the user might realize that it does not respect certain constraints and thus seeks equivalent gadgets with different side effects. The *Similarity Pane* (see Figure 2.E and Figure 6 for details) presents all the gadgets that execute the same operation as the selected one using the dissimilarity matrix presented in Section 4.1. *MultiDimensional Scaling (MDS)* is applied to the matrix to obtain a pair of coordinates for each subset and all the subsets are shown in a scatter-plot, highlighting in green the set containing the selected gadget. Since each point of the scatter-plot represents a set of gadgets, the radius of a point is proportional to the cardinality of the set that it represents. By clicking on a point of the scatter-plot, the relative set is shown in the *Tree Pane* allowing the user to inspect the contained gadgets in detail.

Adding a gadget to the chain will trigger the recomputation for the registers set so far. By default, the *Registers Pane* is updated to preserve these registers, thus showing in the *Tree Pane* only the gadgets that are safe with respect to already set registers. The current state of the built chain is visible in the *Chain Pane* (see Figure 2.F). The chain is represented as a sequence of rectangles in which each

Figure 6: The *Similarity Pane* shows all the subsets of gadgets that execute the `rdi+=1` operation as the one visible in Figure 5; subsets are displayed in a scatter-plot by applying MDS to the dissimilarity matrix presented in Section 4.1. The size of the points encodes the cardinality of the related subset; **(a)** the green set contains the selected gadget, **(b)** the user has chosen to explore the set that does not modify `rcx` with respect to the first one.

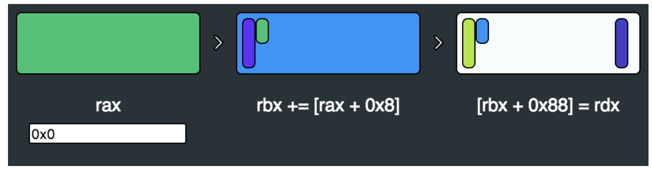


Figure 7: Details of the *Chain Pane* containing a chain of 3 gadgets. From left to right, the first gadget sets a constant value (i.e., `0x0`) in `rax`; the second one dereferences 2 registers: one is already set by the previous gadget (the green rectangle has half height) while the other is not. The third gadget reads from an unset register (visible on the right) and dereferences two others.

rectangle corresponds to a gadget; the background color of the rectangle is the color of the register set by the gadget. Inside a rectangle, registers used by the gadget are shown by distinguishing between dereferenced registers (on the left of the rectangle) and source registers (on the right). These registers are represented as vertical rectangles using the same convention seen for the *dereferenced registers matrix*: full height indicates that the dependency is not satisfied at that point of the chain; conversely, half height indicates that it is. This encoding becomes increasingly important as the chain grows to manage complex dependencies between gadgets. Below the rectangle, the operation of the gadget is reported and, for gadgets that set a register to a value, there is a textbox to specify that value (see Figure 7). The sequence can also be changed by reordering gadgets via drag and drop or by removing them.

Once the built chain is complete, clicking on *Dump* the system will produce a Python script that generates the binary encoding of the chain as shown, for instance, in the right portion of Figure 1.

5 Case Study

In this section we present our case study, showing how ROPMate has been used to produce a ROP chain for a vulnerable program that has been the subject of the SECCON 2017 capture-the-flag[3] security competition [21]. The application is written in Go: as compiled Go programs ship with the language runtime embedded in the binary, such runtime usually represents a rather rich source of gadgets. However, such gadgets come with subtle side effects that are less frequent for instance in gadgets from compiled C programs. Impersonating a red team member, we will build a ROP chain to spawn a shell from the attacked application, as in the running example from Section 2 used to illustrate the ROP technique.

Security Bug. The application is amenable to a buffer overflow originating in the lack of bounds checking on one of its input parameters. Our goal is to show a way to turn this defect into a security vulnerability that could be exploited by an attacker to execute arbitrary code on the machine. A common practice is to try to build a ROP chain that is able to replace the running process with a shell in the hands of the attacker: we will attempt to execute the system call `execve("/bin/sh", NULL, NULL)` as in Section 2.

ROP Chain Structure. To execute the Linux system call implementing the `execve` functionality, we remind the reader that a chain has to place the corresponding system call ordinal `0x3b` in register `rax`, and the three parameters for the call in registers `rdi`, `rsi`, and `rdx`. Also, as the first argument is a pointer to the string `"/bin/sh"`, the chain has to write the string to some memory region and place its address in the corresponding register `rdi`.

Due to complex register dependencies that might arise, in the ROP practice it is common to first assess whether there are fairly

[3] Such competitions propose challenges that reflect real-world problems, but with an artificially higher level of complexity aiming at stressing the abilities of the participants. For instance, binaries may miss some useful ROP gadgets that instead are usually available in real-world programs.

simple gadgets to load values to registers, as this is a operation is prerequisite of most tasks. The builder will then worry about how to make data movements between two registers, or a register and memory. Following this approach, we will build a chain that performs three steps: (i) load constant values to mandatory register destinations for the system call; (ii) write the string `"/bin/sh"` to memory and have its address available for the call; and (iii) trigger the system call using a gadget containing the `syscall` instruction.

Crafting the ROP Chain. A possible chain implementing the attack can be constructed as follows (the case study can be followed live in the provided supplemental video):

1. We start by temporarily filtering out gadgets that perform memory accesses by using the *Avoid Memory* checkbox. This will help us to quickly identify gadgets that are unlikely to make the program crash due to possibly invalid memory operations reducing the number of classes in the *Tree Pane* from 11 to 3.
2. We look into operations from the `LoadConst` class to determine which registers can be initialized with an immediate read from the stack using a single gadget. For this program, we find such gadgets for registers `rax`, `rbp`, `rsi`, and `rcx`. By clicking on the `rax` operation (required to set up the ordinal of the system call), we identify the 6 possible gadgets that implement it and add to the chain the simplest one in terms of memory requirement identifiable by using the *memory requirement bars*. We then repeat the same workflow for the `rsi` operation, required to set up the second argument of the system call, and assign the proper input values to the two gadgets (i.e., `0x3b` and `0x0`, respectively) using the textbox under each newly added gadget in the *Chain Pane*.
3. The *Tree Pane* shows that there are no available gadgets for the remaining registers to set up (i.e., `rdi` and `rdx`), consequently we are forced to resort to gadgets that access memory by removing the *Avoid Memory* filter. We move to setting up `rdi` by typing its name in the *Filter Bar* and ROPMATE presents us with two alternatives. The *dereferenced registers matrix* shows us that both of them dereference `rax` to write to memory, so we choose the first one due to its smaller memory requirement.
4. ROPMATE will highlight for the newly added gadget in the chain a dependency on the contents of `rax`, which we previously assigned with the `0x3b` value. However, `rax` at this point should contain an address such that the memory write performed by the gadget takes place in a safely writable region. To this aim, we change the `0x3b` value for the first gadget with an identifier *valid_address* that will eventually be assigned[4] in the Python script. Finally, we write the constant value that will be loaded to `rdi`: we choose another writable-address identifier *bin_sh_address*.
5. We then proceed by "restoring" the system call ordinal in `rax`: we copy the gadget that loads a constant to it by clicking on the *Analysis Pane*; the gadget is duplicated and added at the end of the chain. We then set its value to `0x3b`.
6. For loading register `rdx` with the third argument of the call, we follow a similar workflow as for `rdi`. Using the *Filter Bar*, 10 gadgets implementing the required `LoadConst` operation can be found: the combination of *memory requirement bars* and *dereference registers matrix* leads us to choose one of the first 3 gadgets that will perform a memory write controlled by `rax`, which we can make happen within the same safe region as for the gadget that sets `rdi`. The required `0x0` value is assigned to the operation, then the gadget is dragged with the mouse right before the one that loads `0x3b` to `rax`, so that *valid_address* will be used for the memory access. At this stage, step (i) has been carried out by the chain.
7. We now need to make provisions to assemble `"/bin/sh"` in the memory location *bin_sh_address* pointed by `rdi`. Using the *Filter Bar*, we type `*rdi` to highlight the relevant gadgets that write to the pointed location. We choose the first operation among the three available as it conveniently reads the value to write from `rax`. Among the 6 possible gadgets for it we choose the one that dereferences only `rdi` as suggested by the *dereferenced registers matrix*. Similarly as when assigning `rdi`, we add a duplicate instance of the gadget that loads to `rax` at the end of the chain, and then we modify the second-last instance of such gadget to hold the required string, which is encoded along with its terminator using the handy Python function `u64("/bin/sh\x00")`. Step (ii) is thus completed.
8. Step (iii) is straightforward: we look for a gadget containing a `syscall` instruction by looking within the `Other` class in the *Tree Pane*, and find a gadget that implements the intended semantics without any side effects. The ROP chain is thus complete, and can be exported to a Python script using the *Dump* functionality.

6 USER EVALUATION

We have conducted a formative user evaluation in order to obtain some preliminary feedback on the general usability and effectiveness of ROPMATE. The involved subjects were 4 ethical hackers having experience in red teaming processes, ROP exploits, and hacking competitions for more than one year.

Participants were first exposed to a practical use of ROPMATE and, after that, they were asked to accomplish some tasks on the system and to express their thoughts, feelings, and opinions while interacting with it. In order to further improve the obtained feedbacks, we have used an evaluation environment [4] that is able to encapsulate ROPMATE and trace the participants' actions.

Concerning the received feedbacks, all participants reported the visual approach to the problem was very useful and user-friendly. In particular, P2 and P3 observed that ROPMATE acted as an interactive recommender for the next gadget to add to the chain. Participant P4, instead, commented that the proposed way to create the ROP chain allowed him to not be overwhelmed by useless gadgets. Furthermore, all participants thought that the interaction technique of clicking and filtering gadgets in the *Tree Pane* was easy to understand and found the classification helpful for searching efficiently the right gadget. Participant P1 and P2 appreciated that the histograms near the classes allowed them to have a visual hint of the number of different operations among which they can choose. Participant P3 expressed some frustration about the dragging of gadgets in the presence of a long chain, and participant P4 commented that it would have been nice to support advanced filters.

This preliminary feedback allowed us to improve the system usability by modifying the visual component of the first prototype: for example, a participant observed that the information of how many gadgets were present in each subset of MDS could be useful for getting an overview of register modifications for a single operation and therefore we added it to the system. The first prototype represented the registers dereferenced by a gadget as a list of colored rectangles. After the evaluation, we changed the list into the matrix representation because some participants asked for a better representation of them in order to better distinguish different registers. Concerning the current state of the built chain, the registers dependency of each gadget was added to the prototype after some participants highlighted the usefulness of this information, specifying also to encode whether the dependency is satisfied or not.

Moreover, the analysis of traces pointed out that users were frequently inspecting the actual size of the gadgets (likely to understand whether they will fit the available stack room for the chain) so we

[4] A natural choice is to pick an address within the `.data` segment.

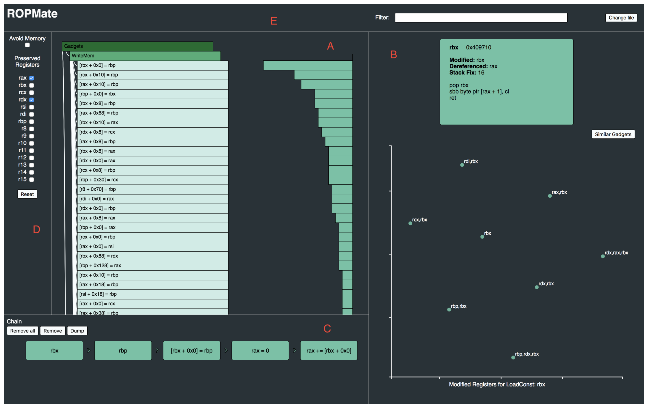


Figure 8: The ROPMATE visual interface before the formative user evaluation.

have added a user configurable threshold to the system triggering a color scale that allows quickly identifying gadgets below the threshold. As a comparative example with respect to Figure 2, Figure 8 shows the ROPMATE interface before the user evaluation.

7 CONCLUSION

Building a ROP chain is not easy: understanding the semantics of each gadget and finding the right one amidst data dependencies and side effects can be a heavy burden in the ROP coding activity.

In this paper we have proposed ROPMATE, a novel Visual Analytics solution specifically designed to assist human red team ROP builders providing a visual interface based on semantically meaningful gadgets that can be filtered according to user needs and chained to form fully-functional exploits. This approach has been demonstrated through an example of usage and a formative evaluation.

In the following, we discuss some limitations of the proposed solution, limitations that will constitute the basis for future work.

Filtering Effectiveness. Although the system include means for filtering the gadgets, it does not support complex filtering activities, being the underlying query language somehow limited.

Gadget Chain Overview. User experience suggests that, the longer the size of the chain, the harder the task of assembling it. As an aid for the construction of long chains, we are currently designing an Overview Pane that allows visualizing the whole chain by preserving its main features while inspecting, on demand, details on gadget subsequences.

Guidance. An interesting future work would be to increase the analytical component in order to suggest some combinations of gadgets that perform a specific operation (possibly selected through a more powerful filtering language). This would allow the user to emulate the semantics of a single missing gadget, with the combination of a few others. Such combination of gadgets would then be added as a whole to the ROP chain. However, implementing such a guidance is not an easy task due to the inherently combinatorial nature of the problem. We regard Progressive Visual Analytics [17] as a promising technique that can provide approximate early results in this context.

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