Exploitation Techniques and Defenses for Data-Oriented Attacks

Long Cheng*, Hans Liljestrand[†], Thomas Nyman[†], Yu Tsung Lee[§],
Danfeng (Daphne) Yao[‡], Trent Jaeger[§] and N. Asokan[‡]

*School of Computing, Clemson University, USA

[†]Department of Computer Science, Aalto University, Finland

[‡]Department of Computer Science, Virginia Tech, USA

§Department of Computer Science and Engineering, Pennsylvania State University, USA

Abstract—Data-oriented attacks manipulate non-control data to alter a program's benign behavior without violating its controlflow integrity. It has been shown that such attacks can cause significant damage even in the presence of control-flow defense mechanisms. However, these threats have not been adequately addressed. In this SoK paper, we first map data-oriented exploits, including Data-Oriented Programming (DOP) attacks, to their assumptions/requirements and attack capabilities. We also compare known defenses against these attacks, in terms of approach, detection capabilities, overhead, and compatibility. Then, we experimentally assess the feasibility of a detection approach that is based on the Intel Processor Trace (PT) technology. PT only traces control flows, thus, is generally believed to be not useful for data-oriented security. However, our work reveals that data-oriented attacks (in particular the recent DOP attacks) may generate side-effects on control-flow behavior in multiple dimensions, which manifest in PT traces. Based on this evaluation, we discuss challenges for building deployable dataoriented defenses and open research questions.

I. INTRODUCTION

Memory-corruption vulnerabilities are one of the most common attack vectors used to compromise computer systems. Such vulnerabilities can be exploited in different ways, which potentially allow attackers to perform arbitrary code execution and data manipulation. Existing memory corruption attacks can be broadly classified into two categories: i) control-flow attacks [1], [2], [3] and ii) data-oriented attacks (also known as non-control data attacks) [4], [5], [6], [7], [8]. Both types of attacks can cause significant damages to a victim system [9].

Control-flow attacks corrupt control data (*e.g.*, return address or code pointer) in a program's memory space to divert the program's control flow, including malicious code injection [1], code reuse [2], and Return-Oriented Programming (ROP) [3]. To counter these attacks, many defense mechanisms have been proposed, such as stack canaries [10], Data Execution Prevention (DEP) [11], Address Space Layout Randomization (ASLR) [12], Control-Flow Integrity (CFI) [13], Return-Flow Guard (RFG) [14], Intel's CET [15] and MPX [16]. In particular, CFI-based solutions [17] have received considerable attention in the last decade. The idea is to ensure that the runtime program execution always follows a valid path in the program's Control-Flow Graph (CFG),

by enforcing security policies on indirect control transfer instructions (*e.g.*, ret/jmp).

In contrast to control-flow attacks, data-oriented attacks [5] change a program's benign behavior by manipulating the program's non-control data (*e.g.*, a data variable/pointer which does not contain the target address for a control transfer) without violating its control-flow integrity. The attack objectives include: 1) information disclosure (*e.g.*, leaking passwords or private keys); 2) privilege escalation (*e.g.*, by manipulating user identity data) [5]; 3) performance degradation (*e.g.*, resource wastage attack) [18]; and 4) bypassing security mitigation mechanisms [19].

As launching control-flow attacks becomes increasingly difficult due to many deployed defenses against control-flow hijacking, data-oriented attacks are likely to become an appealing attack technique for system compromise [20], [6], [19], [7], [21], [8]. Data-oriented attacks can be as simple as flipping a bit of a variable. However, they can be equally powerful and effective as control-flow attacks [22]. For example, arbitrary code-execution attacks are possible if an attacker could corrupt parameters of system calls (e.g., execve()) [9]. Recently, Hu et al. [7] proposed Data-Oriented Programming (DOP), a systematic technique to construct expressive (i.e., Turingcomplete) non-control data exploits. Ispoglou et al. [23] presented the Block-Oriented Programming (BOP), a code reuse technique that utilizes basic blocks as gadgets along valid execution paths in the target binary to generate dataoriented exploits. Though data-oriented attacks have been known for a long time, the threats posed by them have not been adequately addressed due to the fact that most previous defense mechanisms focus on preventing control-flow exploits.

The motivation of this paper is to systematize the current knowledge about exploitation techniques of data-oriented attacks and the current applicable defense mechanisms. Unlike prior systematization of knowledge (SoK) papers [4], [24], [25] related to memory corruption vulnerabilities, our work specifically focuses on data-oriented attacks. In addition to generic memory corruption prevention mechanisms discussed in [4], [24], [25] such as memory safety, software compartmentalization, and address/code space randomization, we mainly discuss recently proposed defenses against data-oriented at-

tacks. In particular, we experimentally assess the possibility of a detection approach based on hardware-assisted control-flow tracing (*e.g.*, Intel PT) against advanced data-oriented attacks. Our technical contributions are as follows.

- * We systematize the current knowledge about data-oriented exploitation techniques with a focus on the recent DOP attacks. We demystify the DOP exploitation technique by using the ProFTPd DOP attack [6] as a case study, and provide an intuitive and detailed explanation of this attack by analyzing its constituent steps. We also discuss representative data-oriented exploits including their assumption-s/requirements and attack capabilities (Section II).
- * We present a three-stage model for data-oriented attacks and discuss defense techniques according to different stages. Then, we provide a comparative analysis of recent defensive approaches specially focusing on data-oriented attacks (Section III).
- * We investigate the possibility of using the hardware-assisted control-flow tracing for program anomaly detection against data-oriented attacks, and study the limitation of protection offered by such approach (Section IV).
- * We experimentally assess the feasibility of a detection approach based on control-flow tracing in particular against DOP attacks. We demonstrate that DOP exploits may generate side-effects on control-flow behaviors in multiple dimensions, and thus are more likely to be detected by a program anomaly detector (Section V). We also discuss some open research problems and unsolved challenges (Section VI).

II. DATA-ORIENTED ATTACKS

In this section, we introduce two categories of exploitation techniques to launch data-oriented attacks (Section II-A). We reproduce a real-world DOP attack against the ProFTPD FTP-server [7] and present a detailed description of the attack to demonstrate how the complex attack achieves rich expressiveness (Section II-B). Then, we map representative data-oriented exploits in the literature to their assumptions/requirements and attack capabilities (Section II-C).

A. Classification of data-oriented attacks

We classify data-oriented attacks¹ into two categories based on how attackers manipulate the non-control data in memory space: 1) Direct Data Manipulation (DDM); and 2) Data-Oriented Programming (DOP).

1) DDM refers to a category of attacks in which an attacker directly manipulates the target data to accomplish the malicious goal. It requires the attacker to know the precise memory address of the target non-control-data. The address or offset to a known location utilized in the attack can be derived directly from binary analysis (e.g., global variable with a deterministic address) or by reusing the runtime randomized address stored in memory [6]. Several types of memory corruption vulnerabilities, e.g., format string vulnerabilities,

buffer overflows, integer overflows, and double free vulner-abilities [25], allow attackers to directly overwrite memory locations within the address space of a vulnerable application. Chen *et al.* [5] revealed that DDM attacks can corrupt a variety of security-critical variables including user identity data, configuration data, user input data, and decision-making data, which change the program's benign behavior or cause the program to inadvertently leak sensitive data.

```
void do_authentication(char *user, ...) {
    int authenticated = 0;
    while (! authenticated) {
      type = packet_read(); // Corrupt authenticated
      /* Calls detect_attack() internally */
      switch(type){
        case SSH_CMSG_AUTH_PASSWORD:
           if(auth_password(user, password)){
             authenticated = 1;
            break;}
        case ...
14
      if (authenticated) break;
16
18
    do_authenticated (pw);
    /*Perform session preparation */
19
```

Listing 1: DDM attack in a vulnerable SSH server [5]

Listing 1 illustrates an example of the attack on decision-making data in SSH server, which was first reported in [5]. A local flag variable authenticated is used to indicate whether a remote user has passed the authentication (line 3). An integer overflow vulnerability exists in the detect_attack() function, which is internally invoked whenever the packet_read() function is called (line 6). When the vulnerable function is invoked, an attacker is able to corrupt the authenticated variable to a non-zero value, which bypasses the user authentication (line 16).

2) DOP is an advanced technique to construct expressive non-control data exploits [7]. It allows an attacker to perform arbitrary computations in program memory by chaining the execution of short sequences of instructions (referred to as data-oriented or DOP gadgets). The idea is to reuse the code in these gadgets for malicious purposes other than the developer's original intent. Similarly, Block-Oriented Programming (BOP) [23] constructs exploit programs by chaining BOP gadgets without violating CFI, where each BOP gadget corresponds to a basic block that contains a DOP gadget. Without loss of generality, we use DOP to represent this exploitation technique, which misinterprets multiple gadgets and chains these gadgets together by one or more dispatchers to achieve the desired outcome.

Typically, a DOP attack corrupts several memory locations in a program and involves multiple steps. To understand the complexity and the expressiveness of the DOP technique, we dissect a real-world DOP attack in Section II-B.

There also exists multi-step DDM attacks, where an adversary exploits memory corruption vulnerabilities multiple times to write data to adversary-chosen memory locations. For example, suppose an attacker needs to change two decision-

¹In this work, we mainly focus our investigation on data-oriented attacks that are caused by memory-corruption vulnerabilities. Data-only attacks that are caused by hardware transient faults or logic errors in code are beyond the scope of this work.

making variables while the vulnerability only allows the attacker to change one value each time. It requires a 2-step DDM. Morton *et al.* [8] recently demonstrated a multi-step DDM with Nginx (listed in Table I). The attack leverages memory errors to modify global configuration data structures in web servers. Constructing a faux SSL Config struct in Nginx requires as many as 16 connections (*i.e.*, 16-step DDM) [8].

Like the DOP attack, a multi-step DDM attack violates dataflow integrity. DDM is a pre-requisite for DOP. However, DOP is much more complex than the multi-step DDM. We summarize their key differences in the following.

- * Gadgets and code reuse. DOP/BOP attacks involve reusing code execution through CFI-compatible gadgets. Multi-step DDM hinges on direct memory writes and does not involve any gadget executions.
- * Stitching mechanism and ordering constraint. In DOP and BOP attacks, how to orderly stitch gadgets to form a meaningful attack is important. Multi-step DDM attacks, e.g., crafting and sending multiple attack payloads to manipulate memory values, do not need any special stitching mechanism (and thus there is no ordering constraint).

A significant contribution by Ispoglou *et al.* in [23] is the block-oriented programming compiler (BOPC). BOPC is the first compiler technique that automates the BOP/DOP attack generation (given the arbitrary memory write vulnerability). With the automatically generated attack payloads by the compiler, an attacker first performs a series of DDMs to modify memory and then launches a BOP/DOP attack by chaining gadgets that leverage memory manipulation via DDMs.

B. Demystifying the ProFTPd DOP attack

We use the ProFTPd DOP attack crafted by Hu *et al.* [7] to illustrate the typical flow of DOP attacks. The goal of this DOP attack is to bypass randomization defenses (such as ASLR [12]), and then leak the server's OpenSSL private key. The private key is stored on the heap with an unpredictable layout, which hinders the attacker from reading out the private key from the heap directly. Though the key is stored in a randomized memory region, it can be accessed via a chain of 8 pointers. As long as the base pointer is not randomized, *e.g.*, when the position independent executables (PIE) feature is disabled, it is possible to exfiltrate the private key by starting from the OpenSSL context base pointer (*i.e.*, a known location of the static variable ssl_ctx) and recursively de-referencing 7 times within the server's memory space.

1) ProFTPd vulnerability: ProFTPD versions 1.2 and 1.3 have a stack-based buffer overflow vulnerability in the sreplace function (CVE-2006-5815 [26]). The overflow can be exploited by an attacker to obtain an arbitrary write primitive. The server program provides a feature to display customized messages when a user enters a directory. The message content is saved in .message file in each directory. It can be edited by any user with write-access to the directory. The .message file can contain special characters (i.e., specifiers) which will be replaced with dynamic content such as time/date and server name by the sreplace function.

For example, the string "%V" in .message will be replaced by main_server->ServerName, and "%T" will be replaced by the current time and date. Changing the working directory with a CWD command triggers the processing of .message file, and subsequently triggers the invocation of the sreplace function. To trigger a memory error in the vulnerable function, the attacker crafts attack payloads to modify the content of the .message file, and then send CWD commands to the server.

```
char *sstrncpy(char *dest, const char *src, size_t n) {
    register char *d = dest;
    for (; *src && n > 1; n--)
      *d++ = *src++:
  char *sreplace(char *s, ...) {
    char *m, *r, * src = s, * cp;
    char **mptr,**rptr;
    char *marr[33], * rarr[33];
    char buf[BUF_MAX] = \{ \ \ \ \ \ \ \ \}, *pbuf = NULL;
    size_t mlen=0, rlen=0, blen; cp=buf;
13
15
      for(mptr=marr, rptr=rarr; *mptr; mptr++, rptr++) {
16
        mlen = strlen(*mptr);
         rlen = strlen(*rptr);
18
         if (strncmp(src, * mptr, mlen) == 0) { // check specifiers
19
           sstrncpy(cp,*rptr,blen-strlen(pbuf)); //replace
         specifier with dynamic content stored in *rptr
           if(((cp + rlen) - pbuf + 1) > blen){
             cp = pbuf + blen - 1; \dots
           } /* Overflow Check */
           src += mlen:
           break:
        }
       if (!* mptr) {
        if((cp - pbuf + 1) > blen){//off-by-one error}
          cp = pbuf + blen - 1; \dots
         } /* Overflow Check */
        *cp++ = *src++;
33
34
   }
```

Listing 2: The vulnerable function in ProFTPd

Listing 2 shows the vulnerable sreplace function. The vulnerability is introduced by an off-by-one comparison bug in line 30, which allows attackers to modify the program memory. A defective overflow check in lines 29-34 is performed to detect any attempt to write outside the buffer boundary. When writing to the last character of the buffer buf, (cp-pbuf+1) equals to blen. Thus, the predicate in line 30 returns false, and the string terminator is overwritten in line 33. Consequently, the string is not properly terminated inside the buffer because the buffer's last character has been overwritten with a non-zero byte. In the next iteration of the while loop, the input blen-strlen (pbuf) of the sstrncpy function becomes negative, which will be interpreted as a large unsigned integer (in line 20). Hence, the invocation of sstrncpy overflows outside buffer bounds into the stack and overwrites local variables such as cp. Both the source (i.e., *rptr) and the destination (i.e., cp) of the string copy function, i.e., sstrncpy in line 20, are under the control of the attacker, where *rptr can be manipulated by the attacker through specifying special characters in .message

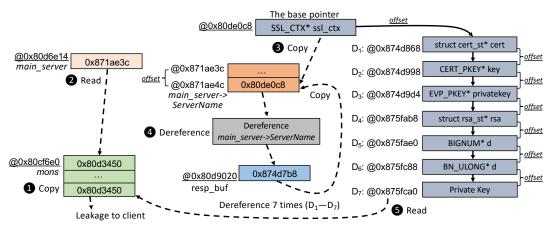


Fig. 1: ProFTPd DOP attack flow. An attacker needs to know the underlined addresses and offsets to launch the attack.

(e.g., "%C" will be replaced by an attacker-specified directory name). As a result, the vulnerability allows the attacker to control the source, destination, and number of bytes copied by subsequent iterations of the while loop in lines 15-35.

2) The attack flow: Fig. 1 shows a step-by-step description of the ProFTPd DOP attack, where the underlined addresses and offsets are required to be known before launching the attack.

The attacker interacts with the server program (over the course of numerous FTP commands) to corrupt program memory by repeatedly exploiting the buffer overflow vulnerability. In this scenario, the command handler cmd_loop in ProFTPd serves as the data-oriented gadget dispatcher. In each iteration, the attacker triggers the execution of targeted gadgets by sending a crafted attack payload to the server program, *e.g.*, the dereference gadget *d++=*src++ located in sstrncpy (line 4 in Listing 2). We reproduced the ProFTPd DOP attack, and observed that the vulnerable function sreplace is called more than 180 times during the attack.

Over the course of the attack, based on the known addresses and offsets (underlined in Fig. 1) extracted from the ProFTPd binary, the attacker systematically corrupts program memory to construct a DOP program out of individual operations. The main steps, shown in Fig. 1, are described as follows.

- To read data from arbitrary addresses in the server, the attacker needs to overwrite string pointers used by a public output function (e.g., send). To this end, the attacker manipulates 12 pointers in a local static mons array located at 0x80cf6e0 to a global writable location (i.e., the attacker specifies this location, denoted by G_PTR). As shown in Fig. 1, the mons array is filled with G_PTR's address 0x80d3450. Thus, when the server returns the date information to the client, it prints the value pointed by G_PTR. This step builds an exfiltration channel which can leak information from the server to the network.
- **9** The attacker knows the memory address of the global pointer main_server at 0x80d6e14, and reads the main server structure address pointed by main_server, *i.e.*, 0x871ae3c. The read operation is implemented by writing the address of the main server structure to the global

writable location G_PTR, and then transmitting the output via the exfiltration channel to the attacker side.

- **②** The attacker knows the offset of the field ServerName in the main server structure, which is 0x10 according to the binary of ProFTPd. Then, the attacker is able to calculate the address of main_server->ServerName, *i.e.*, 0x871ae3c+0x10=0x871ae4c. Given the memory address 0x80de0c8 of ssl_ctx, *i.e.*, the base pointer of a chain of 8 pointers to the private key, the attacker writes this address to main_server->ServerName located at 0x871ae4c.
- 4 Deference the base pointer ssl_ctx, where output is 0x874d7b8. The dereferencing operation dereferences the value currently located at main_server->ServerName, by triggering execution of the dereference gadget in line 4 of Listing 2. The dereferenced value will be copied to a known position in the response buffer resp_buf. Then, the attacker obtains the address 0x874d868 of cert by adding the offset $0 \times b + 0$ to the dereferenced value $0 \times 874 d7 b8$ (D₁ in Fig. 1). After that, the attacker copies the address of cert to main server->ServerName for the next iteration of deference. This step repeats 7 times ($D_1 \sim D_7$ in Fig. 1) following the dereference chain as shown in Fig. 1. The attacker needs to know the offset of the relevant field to the base address in each iteration, which can be derived from the binary or source code. Finally, the final address of the private key is obtained.
- **6** The attacker sequentially reads 8 bytes from the private key buffer via the information exfiltration channel constructed in the first step. This process repeats for 64 times to retrieve a total of 512 bytes data.

C. Representative data-oriented attacks

In the seminal work of non-control data attacks [5] and later FlowStitch [6], the authors have described more than 20 different data-oriented exploits (most of them are single-step DDM attacks). More recently, several research efforts have shown that data-oriented attacks pose serious threats to real-world programs.

| Targeted Application and Year | Туре | Assumption/Requirement | Capability | |
|--|-------------------|---|--|--|
| Chrome [27], 2016 | DDM | Identified security-critical variables, and arbitrary read/write capability | Bypass the same-origin policy | |
| Linux Page Table [28], 2017 | DDM | Kernel code writable, and arbitrary read/write capability | Bypass the kernel CFI | |
| InternetExplorer, Chrome [29], 2017 | DDM | Identified security-relevant variables, and arbitrary read/write capability | Information leakage, bypass the same origin policy, etc. | |
| Nginx [8], 2018 | Multi-step DDM | Identified security-critical data structures, known unused portion of the data section, and arbitrary read/write capability | Disable or degrade services, information leakage, etc. | |
| ProFTPd [7], 2016 | DOP | Memory addresses of multiple involved data, identified gadgets/dispatchers, and arbitrary read/write capability | Private key leakage w/ ASLR | |

TABLE I. Recent data-oriented attacks pose serious threats against real-world programs.

Jia et al. [27] utilized data-oriented attacks to bypass the same-origin policy (SOP) enforcement in the Chrome browser. By manipulating the values of in-memory flags related to SOP security policy checking (which requires an arbitrary read/write privilege), the SOP enforcement can be undermined in Chrome. Davi et al. [28] showed that a data-only attack on page tables can undermine the kernel CFI protection. By manipulating the memory permissions in kernel page entries, the attack makes kernel code pages writable and subsequently enables malicious code injection to kernel space.

Rogowski et al. [29] introduced a new technique, called memory cartography, that an adversary can use to navigate itself at runtime to reach security-critical data in process memory, and then modify or exfiltrate the data at will. They demonstrated the feasibility of data-oriented exploits against modern browsers such as Internet Explorer and Chrome, where possible attacks range from cookie leakage to bypassing the SOP. Morton et al. [8] demonstrated the potential threat of data-oriented attacks against asynchronous web servers (e.g., Nginx or Apache). By manipulating only a few bytes in memory, it is possible that an attacker re-configures a running asynchronous web server on the fly to degrade or disable services, steal sensitive information, and distribute arbitrary web content to clients. The attack consists of multiple steps (i.e., a multi-step DDM). It starts with locating the securitycritical configuration data structures of the server and exposing their low-level state at runtime by leveraging memory disclosure vulnerabilities. Then, an adversary constructs faux copies of security-critical data structures into memory by exploiting memory corruption vulnerabilities. By redirecting data pointers to faux structures, a running web server instance can be re-configured by the attacker without corrupting the controlflow integrity or configuration files on disk. However, in the end-to-end exploits, authors in [8] simulated the arbitrary write vulnerability in the recent version of Nginx, rather than exploiting a real-world vulnerability.

Table I summarizes these recent data-oriented attacks. Because existing CFI-based solutions are rendered defenseless under data-oriented exploits, such threats are particularly alarming. To construct a data-oriented exploit, attackers must have an in-depth knowledge of the vulnerable program's exact memory layout at runtime. In comparison to the DDM attack,

a DOP attack requires non-trivial engineering efforts to chain gadgets for malicious effect.

III. DEFENSES AGAINST DATA-ORIENTED ATTACKS

In this section, we first describe a three-stage model for data-oriented attacks, and a taxonomy of existing applicable defense techniques. Then, we provide a comparative analysis of recent defensive approaches, particularly against data-oriented attacks.

A. Three-stage model for launching data-oriented attacks

Fig. 2 illustrates the abstract view of three stages in dataoriented attacks. To launch such attacks, it starts with triggering a memory error of a vulnerable program (*i.e.*, Stage S1), which empowers an attacker with control of the memory space, *e.g.*, read/write capability. In Stage S2, the targeted noncontrol-data is modified (through either DDM or DOP). In Stage S3, the manipulated data variable is used and takes effect to change the default program behavior. Note that S3 does not necessarily happen immediately after the data manipulation. The back edges pointing from S3 \rightarrow S1 and S2 \rightarrow S1 indicate that an attacker may need to corrupt non-control-data multiple times to achieve the malicious goal.

We discuss requirements in different stages (*i.e.*, the threat model) that are essential to launching a successful DOP attack. The first three requirements apply for DDM exploits.

- * The presence of a memory corruption vulnerability (such as a buffer or heap overflow) in the target program, which allows attackers to modify the content of the application's memory (i.e., write capability). This is a reasonable assumption since low-level memory-unsafe languages (e.g., C/C++) are still in widespread use today due to interoperability and speed considerations, even though memory corruption vulnerabilities are an inevitable security weakness in these languages.
- * Knowing the exact *location of target non-control data in memory*. Due to the wide deployment of exploit mitigation technologies such as DEP and ASLR, it is likely attackers need to first leverage memory disclosure vulnerabilities to circumvent the address space randomization [8]. In this case, an exfiltration channel to achieve information leakage

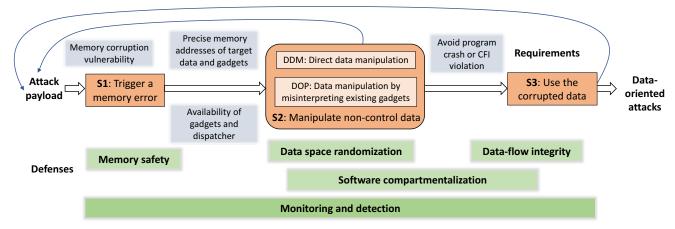


Fig. 2: Stages in data-oriented attacks and mitigation in different stages

is needed (*i.e.*, read capability), such as reading data from arbitrary addresses of the target program.

- * Knowing exactly the *transformation of an attack payload* to the impact on memory space of the target program. For example, a continuous buffer overflow may generate side effects that cause the program to crash. When launching a data-oriented exploit, attackers need to avoid any CFI violation and program crash.
- * Availability of DOP gadgets that are reachable by the memory corruption vulnerability, and triggerable by the attack payload.
- * Stitchability of disjoint DOP gadgets. A gadget dispatcher is needed to dispatch and execute the functional DOP gadgets. However, it is non-trivial to find gadget dispatchers in a program since they require loops with suitable gadgets and selectors controlled by a memory error.

B. Taxonomy of applicable defense techniques

We briefly discuss defenses focusing on preventing these requirements from being satisfied at different points/stages. More generic memory corruption prevention mechanisms (in Stages S1 and S2) can be found in [4], [24], [25].

1) S1 Defense – Preventing exploitation of memory errors: Memory safety enforcement is the first line of defense, which aims to prevent both spatial and temporal memory errors, such as buffer overflows and use-after-free errors. Memorysafe programming languages achieve this with built-in runtime bounds checks and garbage collection that make them immune to memory errors. In contrast, memory-unsafe languages such as C/C++ lack built-in memory safety guarantees. Programs written in memory-unsafe languages therefore commonly exhibit memory errors that may make them vulnerable to runtime exploitation. Enforcing all memory accesses staying within the bounds of intended objects would completely eliminate the pre-conditions for attacks that rely on gaining access to a prohibited area of memory. Despite considerable prior research in retrofitting memory-unsafe programs with memory safety guarantees, memory-safety problems persist due to an trade-off between effectiveness and efficiency: low-overhead approaches usually offer inadequate protection/coverage, while comprehensive solutions either incur a high performance overhead or provide limited backward compatibility [4], [30].

SoftBound [31] and HardBound [32] perform pointer bounds checks against metadata stored in a shadow memory area. SoftBound incurs an average performance overhead of 67% in standard benchmarks. HardBound is a hardwareassisted scheme where the processor checks associated pointer bounds implicitly when a pointer is dereferenced. As the check is performed by hardware logic, the average performance overhead is reduced to around 10%. Both schemes have a worst-case memory overhead of 200%. Fat-pointer schemes store the associated bounds metadata [33] together with pointers, e.g., by increasing their length [34] or by borrowing unused bits from pointers [33]. But changing the representation of pointers in memory breaks both binary and source code compatibility. Code-Pointer Integrity (CPI) [35] provides control-flow hijacking protection with a very low performance overhead (e.g., 8.4% slowdown for C/C++ program). However, it only focuses on code-pointer checking without providing the complete memory safety.

2) S2 Defense – Providing a barrier to access to data or guess memory layout: The purpose of S2 defenses is to mitigate the consequences of attacks in the presence of memory vulnerabilities. S2 defenses include software compartmentalization [36], [37], [38] and address space or data layout randomization [12], [39] techniques. They serve as the second line of defense, which creates a barrier for attackers trying to access target data or guess the memory layout.

Software compartmentalization isolates software components into distinct protection domains in order to limit the utility of existing memory errors (*i.e.*, when the memory error and data to be manipulated exist in different protection domains), but also limit the abilities of a compromised software component. For example, *Software Fault Isolation* (SFI) [36] compartmentalizes software in a single address space by sandboxing untrusted modules into separate fault domains. This compartmentalization ensures that code in the fault domain is unable to directly access memory or jump to code outside the reserved portion of address space, but must

interact with code outside it's domain through well-defined call interfaces.

Randomization aims to hide attack targets by randomizing the layout of memory space [24], [40], [41], layout of the code [42], layout of data [39] or the data itself [43] so that unauthorized access would lead to unpredictable behavior. In particular, data space randomization [39], [44] aims to randomize the representation of data stored in program memory at runtime to make it unpredictable for unauthorized accesses, and thus reducing the possibility that attackers can leak security-critical memory addresses or manipulate the content of targeted data. ASLR [12] randomly chooses the base addresses of the stack, heap, code segment, and shared libraries. Data Space Randomization (DSR) [39] encrypts data stored in memory, rather than randomizing the location. Though strong randomization can stop memory corruption attacks with a high probability, the protection is confined to all data/addresses that are randomized/encrypted. In practice, to avoid a significant performance degradation, not all data/addresses are protected by randomization defenses [4]. On the other hand, information leaks can undermine randomization techniques. In addition, data/address encryption based solutions are not binary compatible (i.e., protected binaries are incompatible with unmodified libraries) [4].

3) S3 Defense – Preventing/detecting use of corrupted data: Data-Flow Integrity (DFI) [47] mitigates data corruption before the manipulation takes effect. Before each read instruction, DFI ensures that a variable can only be written by a legitimate write instruction which can be derived by reaching definitions analysis (i.e., for each value read instruction, it statically computes the set of write instructions that may write the value). However, DFI usually overestimates the set of valid write instructions since the set is statically determined without runtime information. Moreover, Softwarebased DFI incurs a high performance overhead [7] due to the frequent read instruction checking. Intra-procedural DFI incurs 44% and inter-procedural DFI incurs 103% runtime performance overhead, respectively, and approximately 50% space overhead for instrumentation [47]. Hardware-based DFI, e.g., HDFI [46], is efficient, but limited by the number of simultaneous protection domains it can support.

Depending on the granularity of compartmentalization and the boundaries of the security domain, software compartmentalization can also function as a defense in S3. It can prevent the use of corrupted data. For example, when a corrupted pointer is referencing memory in another protection domain, it thwarts the dereference operation.

Szekeres et al. [4] provide a systematic overview of memory corruption attacks and mitigations. They highlighted that though a vast number of solutions have been proposed, memory corruption attacks continue to pose a serious security threat. Real-world software exploits are still possible because currently deployed defenses can be bypassed. Program anomaly detection complements the aforementioned mitigation techniques, and serves as the last line of defense against dataoriented attacks. As shown in Fig. 2, passive monitoring based

program anomaly detection has the potential to detect anomalous program behaviors exhibited in all the three stages of data-oriented attacks. We will discuss its detection capabilities in details in Sections IV and V.

C. Defense mechanisms against data-oriented attacks

In addition to generic memory corruption prevention mechanisms, a number of detection and prevention techniques specially focusing on data-oriented attacks have been proposed in the literature. In this section, we discuss these defenses.

YARRA [20] is a C language extension that validates a pointer's type for *critical data types* annotated by developers, which is an S1 defense. It guarantees that critical data types are only written through pointers with the given static type. YARRA is suitable for hardening access to isolated pieces of critical data, such as cryptographic keys stored in program memory at runtime. However, when applied for the whole program protection, it incurs a performance overhead in the order of 400%~600%. In addition, YARRA relies on the programmers' manual annotations, which is undesirable for complicated programs.

HardScope [21] is a hardware-assisted variable scope enforcement approach to mitigate data-oriented attacks by introducing intra-program memory isolation based on C language variable visibility rules derived during program compilation. On each memory access (i.e., load/store), HardScope enforces that the memory address requested is in the accessible memory areas. Nyman et al. [21] demonstrated the effectiveness of HardScope for the RISC-V open instruction set architecture, by introducing a set of seven new instructions. HardScope instructions are instrumented at compile-time, and memory access constraints are enforced at runtime. It shows that HardScope has a real-world performance overhead of 3.2% in embedded benchmarks. Although HardScope significantly reduces the usefulness of DOP gadgets and thwarts Hu et al. [7]'s example attacks, HardScope cannot guarantee the absence of DOP gadgets in arbitrary programs.

PrivWatcher [45] is a framework for monitoring and protecting the integrity of process credentials (i.e., task_struct that describes the privileges of a process in the Linux kernel) against non-control data attacks. It involves a set of kernel modifications including relocating process credentials into a safe region, code instrumentation and runtime data integrity verification, in order to provide non-bypassable integrity assurances. It ensures the Time of Check To Time of Use (TOCT-TOU) consistency between verification and usage contexts for process credentials by adopting a dual reference monitor model. The authors implemented the PrivWatcher prototype in Ubuntu Linux. The experiment results show that PrivWatcher incurs an overhead less than 3%. But it incurs more than 94% overhead for applications that involve installing new task_struct structures to processes.

Hardware-Assisted Data-flow Isolation (HDFI) [46] extends the RISC-V architecture to provide an instruction-level isolation by tagging each machine word in memory (also known as the tag-based memory protection). The one-bit tag of

| Defense and Year | Stage | Approach | Security Guarantee | Overhead | General Approach |
|------------------------|-----------------------------------|-------------------------|---|----------------------------------|---------------------|
| YARRA [20], 2011 | S1 (Pointer safety) | Program instrumentation | User-specified critical data | 400%~600% (whole program) | ✓ |
| HardScope [21], 2018 | S2 & S3 (Compartmentalization) | Hardware extension | Context-specific memory isolation | ~3.2% | × |
| PrivWatcher [45], 2017 | S2 (Compartmentalization) | Kernel modification | Protect process credentials data in Linux kernel | \sim 3% (94% in extreme cases) | Х |
| HDFI [46], 2016 | S2 (Compartmentalization) | Hardware extension | Coarse-grained data-flow isolation | ~2% | × |
| PT-Rand [28], 2017 | S2 (Randomization) | Kernel modification | Protect kernel page tables | 0.22% | Х |
| DFI [47], 2006 | S3 | Program instrumentation | Data-flow integrity | ~100% | 1 |
| CVI [48], 2018 | S3 | Program instrumentation | Selective data-flow integrity | ~2.7% | Х |

TABLE II. Comparison of defensive mechanisms against data-oriented attacks

a memory unit in HDFI is defined by the last instruction that writes to this memory location. At each memory read instruction, HDFI checks if the tag matches the expected value. However, unlike software-enforced DFI, HDFI only supports two simultaneous protection domains.

Davi *et al.* [28] presented a data-oriented attack against kernel page tables to bypass CFI-based kernel hardening techniques, and subsequently attackers can execute arbitrary code with kernel privileges. To mitigate the threat, they proposed *PT-Rand*, which randomizes the location of page tables to prevent attackers from manipulating page tables by means of data-oriented attacks. Evaluation results show that PT-Rand on Debian only incurs a low overhead of 0.22% for common benchmarks. However, it is still possible attackers undermine these schemes if the secret information (*e.g.*, randomization secret) is leaked or inferred [21].

CVI (Critical Variable Integrity) [48] verifies define-use consistency of critical variables for embedded devices. The define-use consistency is defined as the property that the value of a variable cannot change between two adjacent define- and use-sites. After identifying critical variables (either automatically identified or manually annotated), the compiler inserts instrumentation at all the define- and use-sites for these critical variables, to collect values at runtime and send them to an external measurement engine. CVI checking compares the current value of a variable at every use-site, and the recorded value at the last legitimate define-site. However, like DFI [47], CVI is based on compile-time instrumentation and frequent runtime checking, which incurs a high overhead for the complete protection.

Table II compares representative data-oriented attack specific defensive mechanisms. PrivWatcher [45], HDFI [46], PT-Rand [28], and CVI [48] protect specific non-control data. HardScope [21] can protect against all DOP attacks that violate variable visibility rules at runtime. However, it requires developer assistance in certain settings. The main drawback of HarScope and other solutions based on new hardware extensions [46] is the high bar for deployment. They cannot be directly applied to protect user-space applications against general data-oriented attacks, in particular DOP attacks. On the hand, the two general approaches DFI [47] and YARRA [20] incur a high performance overhead at runtime.

IV. OVERVIEW OF DETECTABILITY BASED ON CONTROL-FLOW TRACING

This and the next sections describe our effort of understanding the data-oriented attacks from the defense perspective. In particular, we consider the scenario where one can efficiently trace control flows. With new hardware development, namely the Intel Processor Trace (PT)², runtime control-flow tracing becomes realistic. Real-time control-flow monitoring without significantly slowing down the program execution can be widely deployed. Control-flow based detectability analysis may sound like an oxymoron, because data-oriented attacks do not violate control-flow integrity. However, this superficial view is incomplete. There exist cases where the anomalies may be detected by correlating or aggregating multiple (legal) control-flow observations.

The necessary condition for detecting a data-oriented attack using control-flow tracing is that the attack directly or indirectly affects the flow of a program's execution. Typically, uses of non-control data in a program can be classified either as predicate uses or non-predicate uses, such as computation uses. A predicate-use directly affects the control flow. While a non-predicate use may affect the computation or the output of a program [49]. Suppose that PT-style control-flow tracing (namely, recording indirect control transfers and conditional branches) is enabled. In what follows, we categorize the cases where data-oriented attacks are impossible to detect (i.e., undetectable cases) and cases where such attacks may be detected (i.e., detectable cases) by control-flow tracing. For the detectable cases, we provide more specific experimental observations in Section V. We report our overhead and performance measurement in Section V-D.

A. Undetectable cases

Detecting data-oriented attacks using control-flow tracing requires that an attack manifests incompatible/unusual control-flow behaviors, *e.g.*, incompatible branch behaviors or frequency anomalies. However, when a manipulated variable is only used for computation or output (*i.e.*, non-predicate use), and the exploit does not incur any side effect on control transfers, such an attack is undetectable by PT control-flow

²PT is a low-overhead hardware feature on Intel CPUs that enables the construction of the complete control flows during program execution.

tracing. We list typical undetectable cases, which are mainly direct data manipulation (DDM) attacks.

- * Corrupting user identity for privilege escalation: Simply corrupting user identify data (e.g., UID) may lead to a compromise of the root privilege. However, for an undetectable data manipulation with the privilege escalation, an attacker usually goes after malicious actions once obtaining the new privilege, e.g., launching a shell. Such malicious actions can be easily detected by control-flow tracing.
- * Corrupting configuration data: Corrupting configuration data via format string vulnerabilities may evade PT-based detection, since format string vulnerabilities allow a single memory write without a side effect on control-flow behavior.
- * Constructing exfiltration channels for information leakage: Attackers exploit an existing information outlet (also known as sink functions such as printf or send) for information leakage by replacing the pointer value of the outlet function's parameter with the address of the data to be exfiltrated. Such an attack may not incur any anomalous control-flow behavior.

B. Possibly detectable cases

We observe that data-oriented attacks can potentially cause three types of anomalous control-flow behaviors.

Incompatible branch behavior: Manipulating a predicateuse variable (e.g., decision-making data) can change the default branch behavior of a program. If there exist two correlated conditional branches that are data-dependent on the manipulated variable before and after the data manipulation site, it is likely the data manipulation incurs incompatible branch behaviors that can be detected by controlflow tracing. For example, in Listing 1, the conditional branches in lines 5 and 16 are correlated, since they both are data-dependent on the variable authenticated. Suppose authenticated is corrupted at line 6 and there is no write to authenticated after the data manipulation. As a result, while (!authenticated) in line 5 returns true, but if (authenticated) in line 16 also returns true. We observe an incompatible branch behavior, which is detected when the corrupted variable authenticated is used in line 16 (i.e., in Stage 3 of the attack).

In addition, a continuous buffer overflow may generate side effects on control-flow behavior, which could result in an incompatible control-flow path observable in Stage S2. For example, though the target buffer is not used for predicate-use, some decision-making variables close to the buffer may be inevitably corrupted. We manually analyzed 14 vulnerable programs in a test suite for buffer overflows [50], and found that 5 out of 14 overflows cause side impacts on decision-making variables (*i.e.*, involved in predicate expressions).

In Section V-B, we experimentally characterize the branch correlation behaviors of ProFTPd under the DOP attack and report our findings.

* Macro-level interaction frequency anomaly: In DOP (also BOP) attacks, an attacker normally needs to interact with

- a vulnerable program to repeatedly corrupt variables to achieve the attack purpose and avoid segmentation faults. This attack activity inevitably results in frequency anomalies during the client-server interaction, which can also be captured by control-flow tracing. For example, in the ProFTPd DOP attack introduced in Section II, an attacker needs to send a large number of FTP commands with malicious inputs to the ProFTPd server to corrupt the program memory repeatedly.
- * Micro-level control-flow frequency anomaly: Short control-flow paths may exhibit unusual execution frequencies. For instance, corrupting variables which directly or indirectly control loop iterations can cause such frequency anomalies. Micro-level control-flow frequency anomalies may be observed in different stages of data-oriented attacks. In addition, control-flow bending (CFB) attacks [9] and resource wastage attacks [18] may also lead to unusual control-flow frequencies.

In Section V-C1, we experimentally compare the frequency differences of both the macro-level interactions and micro-level control-flows in normal ProFTPd executions and under a DOP attack.

V. CHARACTERIZATION OF DOP BEHAVIORS WITH PT

In this section, we provide more concrete observations about DOP's detectability based on control-flow tracing. Specifically, we experimentally measure the execution patterns of the ProFTPd DOP attack on a computer with Processor Trace (PT) enabled. The ProFTPd DOP attack is the only publicly demonstrated end-to-end DOP attack [7]. Our goal is to illustrate the DOP's non-negligible impact on PT traces, as opposed to proposing a specific anomaly detection system.

We organize our experiments according to the detectable cases discussed in Section IV. Our experiments mainly aim to answer the following research questions (RQs).

RQ1: Does the ProFTPd DOP attack exhibit any incompatible branch behavior? How feasible of using branch correlation for detecting incompatible branch behavior in real-world programs. (Section V-B)

RQ2: Does the ProFTPd DOP attack exhibit any frequency anomalies that can be captured by PT tracing? (Section V-C) **RQ3:** What is the runtime performance overhead of PT tracing when monitoring the ProFTPd server? (Section V-D)

We ported the original ProFTPd DOP attack to a 32bit Ubuntu 16.04 with PT support. The attack heavily relies on the precise knowledge of the library and memory layout. In particular, we modified the original metasploit module and created an automated script to scan the ProFTPd binary, which automatically locates the targeted memory addresses. This porting effort was non-trivial³. Our testing platform for the experiments is a desktop computer with an Intel i7-8700 CPU and 32GB of RAM unless otherwise specified. We collected control-flow traces using the Linux Perf-PT tool.

³The automated script of launching the ProFTPd DOP attack, our LLVM-based analysis tools, and all traces of the case studies are provided at https://goo.gl/5hmaZH

A. Tracing indirect and conditional branches with PT

In this section, we briefly explain what control-flow information PT records, which is needed to understand our experimental results. PT tracing is at the instruction level, which is much more fine-grained than system- or function-call level tracing. To capture control-flow information, PT records target addresses of indirect branches (*i.e.*, TIP packets/events for the indirect call, indirect jmp, and ret) and taken/non-taken decisions of conditional direct branches (*i.e.*, TNT packets/events). The trace format in PT is highly compressed to achieve efficient logging at runtime. For example, it uses one bit to indicate taken or not-taken for a conditional branch.

Recent research has shown PT's applicability for on-line security enforcement to defend against control-flow attacks (referred to as dynamic CFI solutions). GRIFFIN [51] is an operating system mechanism (running in the kernel) that leverages the PT feature to enforce CFI policies. PT-CFI [52] and FLOWGUARD [53] are two backward-edge control-flow violation detection systems using PT tracing. To address the over-approximation problem of control targets in forward-edge CFI, PITTYPAT [54] utilizes PT to track basic block execution to compute the legal control transfer target sets through runtime path-sensitive point-to analysis. But PITTYPAT still makes approximations, as an incomplete execution context is used in its points-to analysis. μ CFI [55] improves PITTYPAT by recording full execution context with PT to perform an accurate points-to analysis, and thus getting a unique code target for each indirect control-flow transfer.

However, none of these existing work investigates the PT-based detection against data-oriented attacks. In what follows, we look into the possibility of PT-based detection against DOP attacks, which can also be applied to detect DDM attacks.

B. RQ1: Branch behavior patterns

We first utilize correlations among branches to spot incompatible branch behavior in the ProFTPd DOP attack. Then, we characterize the branch correlation in benchmark programs to show the feasibility and generality of this approach.

We define the *subsume* and *mutually exclusive* deterministic relations among branch conditions/predicates. If a branch condition BR_i returns true/false, another branch condition BR_j must return true/false, we say BR_i subsumes BR_j . BR_i and BR_j are mutually exclusive, if they always return different results. For example, (x>10) subsumes (x>5), and (x>10) and (x<5) are mutually exclusive.

1) Identifying branch correlation in ProFTPd DOP: For ProFTPd's vulnerable function sreplace (Listing 2), the conditional branches in lines 21 and 30 of Listing 2 are correlated. Both are data dependent on the same variables cp, pbuf, and blen. Fig. 3 shows these two correlated branches, denoted as BR₁ and BR₂, respectively.

Take the example in Fig. 3, we could use the satisfiability modulo theories (SMT) solver Z3 [56] to determine any subsume or mutually exclusive relationship between correlated branches. If the SMT solver could not find a solution for the combined constraints (BR₂) and Not(BR₁) (*i.e.*, the logical

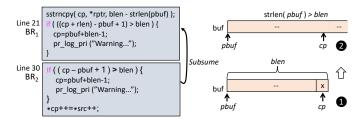


Fig. 3: Branch correlation and an incompatible branch behavior in the ProFTPd DOP attack

not of BR_1), we derive that BR_2 subsumes BR_1 . In order to derive the subsume relationship from BR_2 to BR_1 , we first add the predicate BR_2 as a constraint into Z3 solver. However, cp gets redefined in line 31 (Listing 2), which is true-control-dependent on the branch in line 30. Thus, we need to replace BR_2 with the statement in line 31 as the constraint, i.e., cp==pbuf+blen-1. Then, we add the constraint Not (((cp+rlen)-pbuf+1)>blen) to the solver. Because the variable rlen is the length of a non-null string (derived from the source code), we add rlen > 0 as an additional constraint. At the end, the solver returns unsat (satisfiable), and thus we derive that BR_2 subsumes BR_1 , i.e., if BR_2 returns true, BR_1 should also take the true branch.

- 2) Incompatible branch behavior in ProFTPd DOP: During the course of the ProFTPd DOP attack, the attacker first triggers the memory corruption error in sreplace, by filling up buf (where BR₂ returns true) and overwriting buf's terminator with a non-zero byte (in line 33 of Listing 2), as shown in **0** in Fig. 3. Since buf's last character is a nonzero value, it becomes a non-terminated string. As a result, strlen(pbuf)>blen (@ in Fig. 3), which enables the attacker to corrupt the local variables such as cp and blen in line 20. To bypass the overflow checking in lines 21-27 in the following iterations, the attacker needs to make sure that the predicate in line 21 returns false. From the PT trace, we could observe the predicate in line 21 (i.e., BR₁) takes the false branch. Since BR2 subsumes BR1, and BR2 has taken the true branch, the runtime branch behavior of BR1 and BR₂ are incompatible. Note that the observed incompatible branch behavior is not specific to DOP attacks. For any DDM attack against the ProFTPd, as long as the attacker exploits the same vulnerability (CVE-2006-5815 [26]), we could observe this incompatible branch behavior.
- 3) Branch correlation in benchmarks: Our case study of the ProFTPd DOP attack demonstrates that correlated branches are useful for identifying incompatible branch behaviors. To reflect the possibility of data-oriented attacks to manifest incompatible branch behaviors, we characterize the prevalence of branch correlation in benchmark programs.

In order to capture branch correlations with arbitrary predicate expressions, we define the correlated branches to be branches that have joint data dependency, including *i) direct* data-dependent branches that share at least one common predicate variable; and *ii) indirect* data-dependent branches that use different predicate variables, but they are data-dependent

on at least one common variable. We also define the *simple forms of branches*, where a branch predicate simply compares a variable with a constant value, *e.g.*, the conditional branches in lines 5 and 16 in Listing 1 are simple branches. Previously, Zhang *et al.* [57] used correlation among simple forms of branches to detect infeasible program paths caused by memory corruptions.

We developed a branch correlation analysis tool based on LLVM [58]. Our tool handles *inter-procedural* branch correlations and *arbitrary predicate expressions*. We performed our branch correlation analysis on eight programs. They include four Linux utility programs (flex, grep, gzip, sed) from the Software-artifact Infrastructure Repository (SIR) [59] and four vulnerable programs (wu-ftpd, orzhttpd, ghttpd, sudo) from the FlowStitch benchmarks [6].

Table III reports the branch correlation results. Overall, 24% of the branches exhibit simple forms of conditional predicates, and 18% of the branches with simple forms are correlated (including direct and indirect correlations). For the direct correlations with simple forms (*i.e.*, correlated branches use the same predicate variable), we used the SMT logic solver Z3 [56] to determine any "subsume" or "mutually exclusive" relationship. Our results show that for a limited number of branch correlations (around 2%), we can directly derive the deterministic correlation relationship (denoted as "directly derivable simple BRs" in Table III). It also reflects that the branch correlation analysis in [57] has a very limited coverage.

| Application | Total BRs | Correlated BRs | Simple BRs | Correlated Simple BRs | Directly Derivable Simple BRs |
|-------------|--------------|-------------------|---------------|--------------------------|----------------------------------|
| flex | 1142 | 813 (71%) | 557 (49%) | 356 (31%) | 62 (5%) |
| grep | 1664 | 1456 (87%) | 278 (17%) | 216 (13%) | 32 (2%) |
| gzip | 737 | 533 (72%) | 241 (9%) | 169 (23%) | 60 (8%) |
| sed | 1081 | 1017 (94%) | 172 (16%) | 142 (13%) | 12 (1%) |
| wu-ftpd | 2781 | 1943 (70%) | 688 (25%) | 398 (14%) | 84 (3%) |
| orzhttpd | 35 | 23 (66%) | 13 (37%) | 7 (20%) | 0 (0%) |
| sudo | 675 | 499 (74%) | 163 (24%) | 116 (17%) | 0 (0%) |
| ghttpd | 107 | 90 (84%) | 16 (15%) | 11 (10%) | 0 (0%) |
| Average | 1028 | 77% | 24% | 18% | 2% |

TABLE III. Branch correlation analysis in benchmarks

We observed 77% of the branches have at least one correlated branch, *i.e.*, given BR_i , we can find at least one branch $BR_j \neq BR_i$, where BR_i and BR_j have joint data dependency. Though our analysis only captures the coarse-grained branch correlations as opposed to the deterministic relationships among branches, this result suggests the prevalence of branch correlations with complex predicate expressions in a program, which can be potentially used as checkpoints to detect incompatible branch behaviors (*e.g.*, first using symbolic execution or dynamic analysis techniques to identify deterministic relationships among these correlated branches).

C. RQ2: Frequency patterns

We characterize how DOP impacts the quantitative behaviors of ProFTPd by comparing the frequency distributions in DOP attacks and normal executions. We conducted two sets of comparisons, *i*) on macro-level interaction frequencies and *ii*) on micro-level control-flow frequencies. Both are defined in Section IV.

1) Macro-level interaction frequencies: To detect interaction frequency anomalies under the DOP attack, we derived the FTP commands sent from clients by tracing control-flow transfers of the FTP command dispatcher function _dispatch in the ProFTPd server program. PT captures the control-flow transfers from _dispatch to different command handlers, e.g., core_cwd indicates that the command CWD (i.e., change working directory) has been received.

To characterize the baseline FTP interaction frequencies, we used the LBNL-FTP-PKT [60] dataset. It contains all incoming anonymous FTP connections to public FTP servers at the Lawrence Berkeley National Laboratory over a ten-day period, a total of 21482 FTP connections. Each connection session is considered as a behavior instance, and we extract FTP commands in each connection from the dataset.

We computed the frequency distributions of 2-gram FTP command sequences. Each 2-gram transition corresponds to a high-level execution feature. We applied the Principal Component Analysis (PCA) technique for dimension reduction, as such a distribution-based profiling produces a large number of features. We adopted the X-means clustering approach [61] to cluster all behavior instances in baseline FTP command sequences, where the center of each of the X-clusters represents a normal program execution context.

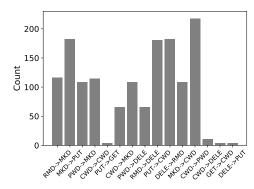


Fig. 4: For macro-level interaction frequencies, 2-gram distribution of FTP commands within a connection during the ProFTPd DOP attack.

Fig. 4 shows the macro-level frequency distribution of 2-gram FTP commands within a connection during the ProFTPd DOP attack. Over the course of the attack, it involves more than 1000 client-server FTP commands. In contrast, the average interactions per session in the normal LBNL-FTP-PKT dataset [60] is 41.

Fig. 5 illustrates the X-clustering for 2-grams of FTP commands with PCA reduction to 3-dimension. The DOP instance (*i.e.*, red triangle) does not belong to any normal clusters (*i.e.*, blue dots). These results suggest that the client-server interactions under the DOP attack drastically differ from the baseline executions.

2) Micro-level control-flow frequencies: The .message file is the input to vulnerable function sreplace. Its content determines the control-flow behaviors in sreplace, which we measure with PT tracing in this experiment. In the ProFTPd

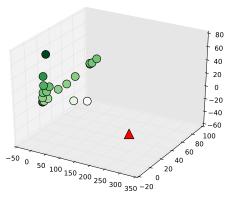


Fig. 5: For macro-level interaction frequencies, X-clustering for 2-grams of FTP commands with PCA reduction to 3-dimension using LBNL-FTP-PKT dataset [60]. The DOP attack involves an abnormally high number of client-server interactions.

DOP attack, an attacker crafts .message (i.e., as malicious payloads) to repeatedly fill up the allocated buffer and write bytes beyond the buffer in sreplace, which exhibits anomalous behaviors of control-flow transfers. We defined all control-flow transfers in each sreplace invocation as a behavior instance, following the approach in [62]. Since it is difficult to harvest .message files from old version FTP servers, in this experiment, we randomly generated 1000 .message files without triggering the overflow as the baseline executions. For each .message file, we inserted a character string⁴ with random length less than 100 nonspecifier characters and then appended a random specifier (out of 20 different specifiers defined in ProFTPd). We repeated this process with random rounds up to 10 times to generate a .message file.

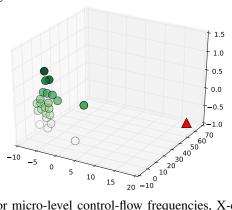


Fig. 6: For micro-level control-flow frequencies, X-clustering for 2-gram control-transfers with PCA reduction to 3-dimension in sreplace. The DOP attack exhibits a unique pattern of control-flow transfers in comparison to baseline executions.

The feature extraction and dimension reduction procedures are similar to the macro-level analysis described above. After applying PCA, we reduced the original high-dimensional data to 3-dimensional data and then performed the X-clustering. Our result comparing the control-flow frequency properties in sreplace is shown in Fig. 6. The baseline dataset is clustered into 23 clusters. Similar to Fig. 5, the DOP instance is an obvious outlier. The distance between the DOP instance and any normal cluster is significant, where the average distance is larger than 60-unit length in the 3D space.

D. RQ3: Tracing Overhead

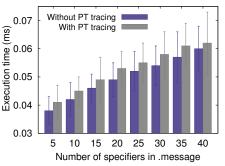


Fig. 7: Tracing overhead of the sreplace function. PT tracing constantly incurs a low overhead ranging from 3.3% to 7.8% slowdown in different settings.

To measure the PT tracing overhead (*i.e.*, Linux Perf-PT), we instrumented the ProFTPd server program with execution time measurement functions at entry and exit points of the vulnerable function sreplace, and the FTP command handler function cmd_loop, respectively. We compared the execution time of sreplace as well as the execution time of processing an FTP command with and without PT tracing. All the results have been averaged over 1000 runs, and the related standard deviations are provided as error bars.

The control-flow behavior in sreplace depends on the number of specifiers and non-specifier characters in the .message file. In this test, we changed the number of specifiers from 5 to 40 and fixed the length of non-specifier characters to 100 in each .message file. With increasing the number of specifiers, sreplace takes more time to replace these specifiers with dynamic content. Correspondingly, the number of control-flow transfers involved in sreplace increases from 3181 to 4323. Fig. 7 shows that the PT tracing overhead is constantly low in different settings. We observed that Perf-PT tracing incurs a low overhead ranging from 3.3% to 7.8% slowdown. Processing an FTP command incurs around 2.1% slowdown (the average execution delay with and without PT tracing is 0.191ms and 0.187ms, respectively).

The tracing storage overhead is linearly proportional to the number of control-flow transfers during the program execution. To trace control-flow behaviors of sreplace, the size of decoded PT traces ranges from 25.5KB to 34.6KB as the number of specifiers increases from 5 to 40. The low-overhead tracing by PT increases the feasibility for practical deployment of program anomaly detection.

We also experimentally compared the tracing slowdown performance of Perf-PT against three commonly used

⁴The content of non-specifier character string does not impact on the control-flow behavior in sreplace, which blindly copies non-specifier characters to the output buffer.

system-call tracing tools including PIN, SystemTap, and Strace [62]. We measured the elapsed time between the entry and exit points in three utility applications (*i.e.*, tcas, replace, and schedule) from the Software-artifact Infrastructure Repository (SIR) benchmark suite [59] on a desktop computer (Ubuntu 16.04, Intel i7-8700 and 32GB of RAM).

| Application | Baseline | PIN | SystemTap | Strace | Perf-PT |
|-------------|----------|----------|-----------|---------|----------|
| tcas | 0.008 ms | 17.59ms | 0.009ms | 0.020ms | 0.009ms |
| replace | 0.038ms | 39.311ms | 0.039ms | 0.079ms | 0.040 ms |
| schedule | 0.047ms | 59.108ms | 0.050ms | 0.086ms | 0.049ms |

TABLE IV. Average tracing overhead of different tracing tools

The average tracing overhead results out of 1000 runs are shown in Table IV. The baseline refers to the execution time without tracing. It shows that Strace tracing incurs 113% slowdown on average, and PIN incurs a rather significant runtime overhead because of the dynamic binary instrumentation. SystemTap and Perf-PT show comparable tracing overhead less than 10% in our test. This is because there are a limited number of system-call invocations in these three programs, and thus the binary instrumentation in SystemTap does not introduce too much overhead. However, SystemTap requires a very long instrumentation delay before the program execution. Perf-PT captures all control-flow transfers and thus provides a finer tracing granularity the system-call tracing.

In addition, we measured GRIFFIN's [51] (a customized PT tracing tool in the Linux kernel) tracing overhead on another Intel PT machine (Intel Core i7-7700 CPU and 32GB of RAM). When tracing sreplace of ProFTPd, we observed 4.33%~8.57% (with a standard deviation ranging from 0.004ms to 0.006ms) runtime overhead from GRIFFIN, which is consistent to the results using Perf-PT. Since both Perf-PT and GRIFFIN follow a trace-all-and-then-filter strategy, their slowdown overhead for tracing the whole program or selectively tracing particular memory regions show very close results. We did observe certain PT startup overhead. This one-time PT startup overhead is expected to be amortized across the entire span of the program execution.

Summary of findings.

- * Branch correlations. In ProFTPd's vulnerable function sreplace (Listing 2), we observed an incompatible branch behavior, which exposes the DOP's attack footprint. We also developed a branch correlation analysis tool to demonstrate branch correlations with complex predicate expressions are somewhat prevalent in benchmark programs. These results suggest that the approach of enforcing the branch correlation integrity (which is a principled defense mechanism), with PT-based branch tracing, could be useful to defend against data-oriented attacks.
- * Macro-level and micro-level frequencies. The ProFTPd DOP attack exhibits drastically different frequency distributions. An attack session triggers the sreplace function more than 180 times. It involves >1000 client-server FTP commands, while the average interactions per session in the normal LBNL-FTP-PKT dataset is 41. The normal and DOP

- traces (2-gram distributions of PT traces) exhibit strong differences in simple PCA-and-clustering analysis.
- * Runtime and storage overheads. Our performance evaluation with Perf-PT and GRIFFIN shows that PT's tracing overhead is acceptable, under the trace-all-and-then-filter strategy. The storage overhead is linearly proportional to the number of control-flow transfers during the program execution. With only tracing selective functions or memory regions, the storage overhead is expected to be affordable (in practice, PT log is usually configured as a circular buffer).

VI. CONCLUSION AND FUTURE RESEARCH OPPORTUNITIES

In this SoK work, we systematized the current knowledge on data-oriented exploits and applicable defense mechanisms. We experimentally explored the possibility of using low overhead tracing techniques, namely PT, for characterizing data-oriented attacks. We hope that this systematization will stimulate a broader discussion about possible ways to defend against data-oriented attacks. We highlight some interesting future directions in this area.

Automation of Small Footprint DOP Attacks. An interesting research direction is how to minimize the footprints (i.e., side effects) of a DOP attack while achieving the same attack goal. Our experiments in Section V showed that DOP alters the correlation or statistical properties of control flows. Our empirical study using the FlowStitch benchmarks [6] revealed that on average 43% data-oriented gadgets are involved in at least one conditional branch. Gadgets may have different impacts on control-flow behaviors. Attackers may prefer dataoriented gadgets that cause a minimum deviation from normal executions. Such a selection process requires automation to be efficient. Besides automation, one also needs to define metrics to measure the footprints, i.e., the amount of alteration caused by a DOP execution. Ispoglou et al. [23] made the first step towards automating data-oriented programming through a powerful Block Oriented Programming Compiler (BOPC). Searching for gadget chains under specific constraints is a new research direction.

Assessment of Programs' Susceptibility to Data-Oriented Attacks. Such a characterization – statically or dynamically – would help one understand the threats that CFI cannot protect against. A promising direction is to quantify the degree of control-flow decisions that are dependent on adversarially controlled data (e.g., user input). Such a characterization also helps prioritize the defense effort, enabling one to address programs with the highest susceptibility first.

Low False Positive PT-based Anomaly Detection. DOP attacks exhibit occasional anomalous execution behaviors at runtime, as we have demonstrated in Section V. However, to design a successful anomaly detection solution targeting DOP, much more work is needed. Specifically, one needs to show the instruction-level detection does not trigger many false positives in normal executions. Virtually all existing learning-based program anomaly detection demonstrations are at the higher

system-call and method-call levels. Reasoning instruction-level PT traces for anomaly detection is challenging.

Deep Learning for Control-Flow Behavior Modeling. Noncontrol data violations may involve control flows in multiple locations that are far apart. How to detect incompatible control-flow paths, given a relatively long control-flow sequence, is challenging. Exploring deep learning techniques, such as Long Short-Term Memory (LSTM), may be promising, as LSTM keeps track of temporally distant events.

Selection of Tracing Checkpoints. Due to the storage constraint, it is probably impractical to monitor the complete control-flow transfers of a program. Given a limited overhead budget, how to systematically determine strategic checkpoints for tracing (e.g., setting filters to monitor key functions) would be useful in practice.

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