Selfie: User-defined Sensitive Memory Protection and Recovery

Pengfei Sun
Rutgers University
pengfei.sun@rutgers.edu

Saman Zonouz
Rutgers University
saman.zonouz@rutgers.edu

Abstract—Different users always have different requirement for sensitive memory definition. It is not flexible for aborting program execution once detecting memory corruption. Because the users may lose some sensitive data. We presented Selfie, a hybrid solution to provide one flexible solution to protect the sensitive memory according to users’ requirements in runtime. Finally, Selfie can provide one solution to decide whether execution needs to be recovered. If the memory corruption doesn’t belong sensitive memory, Selfie provides symbolic solver that can help figure out whether the memory corruption can affect the sensitive memory in future.

I. INTRODUCTION

Many programs are still written using type-unsafe languages such as C and C++ for performance and compatibility reasons. However, these languages don’t provide intrinsic guarantees about memory safety [1], [2], [3]. Lack of memory safety, in turn, forms the basis for attacks in the form of code injection [4] and code reuse [5]. Once memory errors happen, the interesting sensitive memory need to keep integrity and recovery from users view. Most time, memory corruption can damage the memory integrity. Memory corruption occurs when a program breaks type safety and writes to an unintended location, potentially corrupting the data. Because all memory locations are equally accessible to all store instructions in a program, current approaches to providing safety from memory corruption in C and C++ require that every store in a program be either statically or dynamically checked for correctness. That means it will incur source code or binary code modification. As a result, there are significant challenges to existing approaches that limit their practical application.

Assuming the source code is available, it is not easy for developers to define sensitive memory for users. Because different users always have different views for sensitive memory. Especially, if the developer makes too much protection which will increase the performance overhead. Meanwhile, most of time, it is impossible for users to get the source code of commercial software. So it is not practical to custom the sensitive memory protection. Even if there are good solution to define the sensitive memory for different users, the another challenge will be how to detect the memory corruptions and recognize whether the memory corruptions will affect the sensitive memory and whether the clean state before memory corruptions need to be recovered. There already are many solutions about how to detect memory corruptions. A number of approaches that attempt to provide type and memory safety for C and C++ programs are fail-stop, aborting program execution once detecting an error [6], [7], [8]. Valgrind [9] use binary rewriting or emulation to dynamically detect memory corruptions in unaltered programs. Diehard [10] is a runtime system that can provide probabilistic memory safety. Fail-stop means the user will lose all sensitive memory once memory corruptions. However, memory corruptions detection are not the only requirements for users. The importance is how to response and protect the sensitive memory when there are memory corruptions. Sensitive memory deletion is good to avoid sensitive data leaking, however, in some sense, it is not good for users when they don’t have any copies for the sensitive data.

In this paper, we present an alternate approach to reducing the impact of sensitive heap memory corruptions on C and C++ programs without modifying source code information or rewriting binary. Because most of sensitive data is in the heap. So we focus on heap memory not stack. Our main contributions are as follows:

• Selfie provide one flexible sensitive memory protection and recovery solution without modifying source code and rewriting binary. Selfie provide one modified memory allocator for C and C++ programs, which can be loading in runtime according to users’ requirements which memory should be sensitive.

• Selfie analyze the possible heap memory corruption vulnerabilities. Selfie balance the pin tool to provide a practical solution to detect the memory corruptions. The importance is to figure out the root cause of the memory corruptions. So Selfie provides data structure extracting and dynamic program slicing to figure out the root cause of the memory corruptions.

• Selfie provide one solution to decide whether execution needs to be recovered. If the memory corruption doesn’t belong sensitive memory, Selfie provides symbolic solver that can help figure out whether the memory corruption can affect the sensitive memory in future. Finally, Selfie can do execution recovery according to the above analysis.

II. HEAP MEMORY CORRUPTION

There are a lot of memory corruption vulnerabilities in software. Heap memory corruption is very serious vulnerability currently. Out there in the wild, many memory allocators are available, such as dmalloc, jemalloc, tcmalloc, malloc(glibc). The whole of paper will base on glibc malloc heap memory allocator. It will be easy to expand to other memory allocators.
Next, we will do simple introduction about glibc malloc memory allocator. And then we talk about the current heap memory corruptions.

A. Heap Memory Allocation

Each memory allocation is internally represented by chunk. A chunk consists of metadata and the memory returned to the program. All these chunks are saved on the heap, which is a memory region capable of expanding when new memory is requested. Similarly, the heap can shrink once a certain amount of memory has been freed.

```c
struct malloc_chunk {
    INTERNAL_SIZE_T prev_size;
    INTERNAL_SIZE_T size;
    struct malloc_chunk* fd;
    struct malloc_chunk* bk;
    struct malloc_chunk* fd_nextsize;
    struct malloc_chunk* bk_nextsize;
};
```

For allocated chunk in heap, the memory layout of the heap is as follows:

- **prev_size**: If the previous chunk is free, this field contains the size of previous chunk. Else if previous chunk is allocated, this field contains previous chunk’s user data.
- **size**: This field contains the size of this allocated chunk. Last 3 bits of this field contains flag information.
  - `PREV_INUSE(P)`: This bit is set when previous chunk is allocated.
  - `IS_MAPPED(M)`: This bit is set when chunk is mmap’d.
  - `NON_MAIN_arena(N)`: This bit is set when this chunk belongs to a thread arena.

B. Heap Memory Corruption Classification

For heap memory corruption, it will involve two regions of memory, one source chunk and one or more target chunks. Target chunks can include application data or heap metadata. The attacker’s goal is to overwrite some part of target chunk with attacker-controlled data. However, this is not only heap memory corruption. We do the deeper study about heap memory exploitation in the following.

Inter-chunk heap overflow involves two regions of memory, and it can be the most common vulnerability class, writing linearly off the end of a heap allocation. There was one very famous case off-by-one heap overflow in glibc [11]. This case can make heap end up in a deterministic state at the time of the exploit attempt. However, far more common is where the attacker is attacking a heap which is in a completely unknown state, such as in the context of a remote service, a web browser renderer process or a kernel.

Intra-chunk heap overflow [12] can provide a very powerful exploitation primitive. This memory corruption does not cross a heap chunk, and it just crosses the fields in the data structure. In this attack, all of the uncertainty and non-determinism arising from unknown heap state is eliminated. The heap can be in any state, yet the same program data will always be corrupted in the same way. Let us to see one code sample as follows. This simple code shows us that intra-chunk heap overflow is very powerful and reliable. And it is also very difficult to detect this memory corruption.

```c
struct goaty {char name[8]; int should_run_calc;};
int main(int argc, const char* argv[]){
    struct goaty* g = malloc(sizeof(struct goaty));
g->should_run_calc = 0;
strcpy(g->name, *projectgoat*);
if (g->should_run_calc) execl("/bin/gnome-calculator", 0);
}
```

Use-After-Free is a very serious and reliable exploit. The reason is that their existence is a result of the combined actions from different parts of an application namely, the parts of the code that can cause the freeing of the object and the parts of the code that use the object. Use-after-free heap memory corruption requires a thorough code review to be identified manually especially in complex and large codebases.

III. SELFIE OVERVIEW

Sensitive memory is different with critical memory [13] which allows programmers to identify and protect data that is critical to the correct execution of their application. In some sense, the programmers can pre-define the sensitive memory. However, different users may have different requirements for sensitive memory. So it is better to define the sensitive memory by users.

Selfie can allow users to choose the sensitive memory in runtime. Whenever the users think about some content that should be sensitive, they can tag the memory that should be sensitive in the time window. When Selfie detects there is one heap memory corruption, the first thing will be to decide whether the memory corruption belongs to the sensitive memory. If it is sensitive memory, we must do execution recovery. If it is non-sensitive memory, we need firstly to figure out whether the memory corruption will affect the sensitive memory in future and then consider whether execution recovery is necessary.

Figure 1 presents the high-level overview of Selfie and details its five main components: (i) a modified memory allocator, (ii) dynamic instrumentation detection tool, (iii) a root cause analyzer, (iv) a symbolic solver and (v) execution recovery.

Selfie relies on a modified memory allocator to collect the sensitive memory. If Selfie does LD_PRELOAD for this modified memory allocator, it will replace the memory allocator in the beginning. So the whole of memory will be sensitive. So Selfie provides runtime libhijack feature which can make users to define which memory will be sensitive in runtime. Dynamic instrumentation tool will continue to check whether there are memory corruptions. Once memory corruptions happen, dynamic instrumentation tool will provide information whether it belongs to sensitive memory or non-sensitive memory. If it is non-sensitive memory, it doesn’t mean we don’t need consider this memory corruption. We need to figure out whether it can affect the sensitive memory by symbolic solver in future. If it does affect or it is sensitive memory, the root cause analyzer will figure out which data structure has been corrupted and...
Fig. 1: Overview of Selfie

which input make the memory corruption. Once Selfie figures out the root cause, Selfie can locate the clean state and then do execution recovery.

IV. USER-DEFINED SENSITIVE MEMORY

Developers can define the critical memory based on the program logic. However, whether the memory is sensitive for users, and it can be different according to different users’ requirements and different contexts. Let us think about one very simple case - text editor ‘geany’. Geany provides many editor windows for different files at the same time. It is not practical for developers to make all editor windows sensitive. So the better solution is that the users can choose which editor window should be sensitive or include sensitive memory for users. Selfie provides one modified memory allocator to help users to define which memory should be sensitive in one time window and provide one tool to help user turn on/off the sensitive memory option.

A. Modified Memory Allocator

Currently, Selfie focuses on glibc memory allocator (e.g. malloc, calloc and realloc). Selfie’s goal is to avoid memory corruption for sensitive memory, and we don’t consider whether the sensitive memory will leak. So we don’t provide isolation or shadow memory for sensitive memory. We keep the sensitive memory integrity and we don’t lose the sensitive memory once memory corruption.

Selfie overrides the glibc memory allocator and adds landmark to the end of the allocated memory. Dynamic instrumentation module can figure out whether the memory is sensitive memory based on the post landmark. Especially, symbolic solver needs to figure out whether there are illegal write to sensitive memory.

B. Switch for Sensitive or Non-Sensitive

If users adopt the modified memory allocator in pre-load section, the whole heap memory will be sensitive and users cannot decide when to turn on/off the sensitive memory. So Selfie can provide the runtime libhijack to override the glibc memory allocator in runtime.

Selfie balances the libhijack to do good thing, change modified memory allocator in runtime. We really don’t do code injection. Instead, Selfie allocates a new memory mapping and store auxiliary data in mapping, such as lib.so and name of the function to hijack. Libhijack will call dlopen and dlsym and replace GOT entry with entry found via dlsym. The key point is about how to re-implement dlopen. The high level will be load dependencies (deps can be loaded via real dlopen). And then it can create memory map and write .so data to new memory maps. Patch into the RTLD and run init routines can be the best way to figure out the address of GOT. Hijack GOT is the best way to override the memory allocator. Once the users want to disable the sensitive memory, Selfie just load the normal memory allocator.

V. ROOT CAUSE FOR HEAP MEMORY CORRUPTION

It is always a challenge task to figure out the root cause for memory corruption. Especially, it is expensive to collect and store dynamic traces which may be needed to locate the memory corruption. Fine-grained tracing is needed so that the fault can be later analyzed and the root cause of the memory corruption can be detected. However, it is far more practical. Selfie integrates online dynamic and offline static analysis to figure out the root cause of memory corruption.

A. Heap Memory Corruption Detection

There has been many solutions [14], [15], [16] about how to detect the heap memory corruption. Selfie adopts dynamic
Selfie’s plugins use LibClang and LibTooling libraries to files and generate the corresponding abstract syntax trees. Selfie uses the Clang compiler front-end to parse the source addresses with their fine-grained data types, Selfie needs to build one clang plugin to automatically figure out the related structure name and definition according to line number. Selfie with source code. How to automatically figure out the data assume the application with debug information. So it will C. Corrupted Data Structure Extract of memory corruption in future. Selfie use the concolic execution which is a technic that execution and sensitive memory, it is very expense to deal with them. Selfie use the concolic execution which is a technic that uses both symbolic and concrete execution to solve a constraint path. The concolic execution is mainly used to cover the effect of memory corruption in future.

Dynamic Slicing

Data structure information let us know which data structure meets memory corruption. However, we still don’t know which input or which step introduces the memory corruption. If we cannot figure out this problem, it will be very difficult to locate the clean state and do execution recovery. It is impossible to analysis each instructions from the beginning. It is better that we can just analyze the related instruction. Selfie uses program slice which contains all statements in a program that directly or indirectly affect the value of a variable or instruction. We can further narrow down the notion of the slice to dynamic program slice [22]. Unlike traditional slicing named static slicing which computes all statements that may have affected the value of a variable at a program point for any arbitrary execution of the program, the dynamic program slicing computes all statements that actually affect the value of a variable/instruction at a program point for a particular execution of the program with given input.

Selfie uses the dynamic program slicing to narrow down the analysis range. The lastest input instruction will be very possible reason for heap memory corruption. Once Selfie recognizes the root cause of memory corruption, Selfie can report where is the clean state, so it can make execution recovery from this clean state and avoid the bad input. Finally, Selfie benefits online dynamic and offline static analysis to do execution recovery not just exit and loose the sensitive memory.

VI. EXECUTION RECOVERY

Memory checkpointing and recovery [23], [24], [25] has been very widely to improve the reliability of today’s software stack. Because it is an important technique that allows users to snapshot the memory image of a running program in main memory and restore the checkpointed image later on. Most application scenarios require high checkpointing frequencies. For example, automatic error recovery techniques typically checkpoint the active memory image at every client request or at carefully selected rescue points, commonly resulting in thousands of checkpoints per second. Selfie takes snapshot based on function level. During the execution, it is possible for Selfie to take a snapshot of the registers and memory states in the entry of each function. Then, at each program point, it is possible to restore the previous snapshot. We don’t means keep all the snapshot, because it will be very expense
for memory. Though we do function level snapshot, we don’t keep all the snapshots. We only focus on source code defined functions. Meanwhile, we analyze the function call graph and choose which function snapshot should be kept following the time window. Figure 3 shows one example about function call graph. We can see main function is the entry, and there are many different exit points. From each entry to exit, it is as one function call path. We keep each path differently. Based on the different paths, we choose whether some function snapshots should be kept.

VII. IMPLEMENTATION

Selfie architecture, as presented in Figure 1, has been implemented on Linux v3.13 for x86_64 Ubuntu 14.04 machine without ASLR. Selfie integrates and modifies current research tools and develops new tools to finish final goal. Runtime libhijack is to balance libhijack [26] which has good support for FreeBSD but not for Ubuntu. I modify the code to make it work well on Ubuntu to load library by dlopen runtime. I modify glibc memory allocator (malloc, calloc and realloc) to add landmark information to override the normal memory allocator for sensitive memory.

Dynamic instrumentation tool is very useful for detecting heap memory corruption. In the beginning, I choose to use PIN [27] to do dynamic instrumentation. Later, I found out another tools Triton [28] which is a Pin-based dynamic symbolic execution (DSE) framework. Although Triton is a DSE framework, it also provides internal components like a taint engine, a snapshot engine, translation of x86 and x86-64 instructions into SMT2-LIB, a Z3 interface to solve constraints and, the last but not least, Python bindings. Based on Triton, Selfie build its own program analysis tool to finish memory corruption detection, symbolic solver and execution recovery. For recording sensitive memory tracing, we build the Read/Write memory tracer based on Triton. So we can know which instruction read or write the sensitive memory. However, runtime tracing based on PIN has super high performance overhead. As one option, I do offline analysis based on IDA Pro. Because we assume without ASLR (it is not good assumption). Selfie use one IDA Pro script to record all heap memory access across an executable using IDA debugger API. So Selfie can build the profile about heap memory access.

Root cause analyzer includes data structure analysis and related instructions analysis. It belongs offline analysis. In Section V-C, we have mentioned that Selfie develop one Clang Libtooling plugin to figure out data structure definition. Before data structure analysis, we firstly use gdb to figure out the line number of error instruction. About dynamic slicing, Selfie balances the Giri [29] which handles both data-flow and control-flow dependences when computing the dynamic backwards slice. Giri takes advantage of the LLVM intermediate representation(IR), which is static single assignment (SSA) form, to reduce the size of the trace file.

Our current Selfie prototype’s detection and recovery is based on Triton dynamic symbolic framework. So it inherit the limitation of Triton.

VIII. EVALUATION

We evaluated Selfie on Intel i7-4710MQ CPU 2.50GHz and 16 GB of RAM. We ran all our tests on an Ubuntu 14.04 Linux kernel 3.13. We designed a set of experiments to verify whether Selfie can be useful in real-world practical scenarios. We firstly go through one simple code example and then target the real-world application.

A. Case study: off-by-one heap overflow

Let us firstly focus on one very simple off-by-one heap overflow, and how Selfie detect the heap overflow and finish the execution recovery. In the following sample, it can have off-by-on heap overflow when n <= BUFF_MAX.

```c
#define BUFF_MAX 128  
int main(int ac, const char *av[])  
{
  char *buff1, *buff2;
  int i;
  buff1 = (char*)malloc(BUFF_MAX);
  buff2 = (char*)malloc(BUFF_MAX);
  int n;
  scanf("%d", &n);
  if (!buff1 || !buff2)
    return -1;
  for (i = 0; i <= n; i++) /* off-by-one */
    buff1[i] = 'A';
  for (i = 0; i <= n; i++) /* off-by-one */
    buff2[i] = 'B';
  free(buff1);
  free(buff2);
  return 0;
}
```

Figure 2 shows that Selfie works well on this simple off-by-one heap overflow. The first time, we set the n value is 128. We can see there are heap overflow and Selfie recognizes the 128 is bad input. So Selfie requests the user to do second time input. When the user input 56 which is n’s value. Now, there isn’t any error. Selfie evaluates the input is good input. We can see that Selfie perfectly detects the heap overflow and then finishes execution recovery. There is many intermediate result about gdb recognizing line number, AST Tree Based on clang libtooling, data structure extracting and dynamic slicing, you can check code package.

B. Case study: NullHttpd

Null httpd is a very small, simple and multithreaded web server for Linux and Windows, Which contains a remote exploitable heap overflow [30], when negative Content-Length values are transmitted. Next, we will show how Selfie detect the heap overflow. In this case study, we will analyze the heap overflow from memory aspect.
In the following, it shows us three pieces of memory dump. In the first piece, it is very easy for us to locate "ef ef ef fe fe fe" which is the landmark to tag the sensitive memory. In the third line, we can find hex sequences "10 67 42 b7" which is the size of calloc(2200). In Section II-A, we have illustrated the metadata about memory allocation, "10 67 42 b7" is the size of allocated memory, and next it will be the allocated memory. The second piece of memory dump show us the heap overflow location. We can check http.c file in line 100. If we just analyze the source code, the size of calloc should be more than 1024, however, the allocated size just 224. So if the buffer is larger than 224, there will be heap overflow. So the reason may locate in in_ContentLength. Because in in_ContentLength is the filed of conn[uid].dat (data structure analysis gives us more information about this data structure), If we find out the conn[uid].dat heap location, we can figure out the value of in_ContentLength. In third piece of memory dump, we find out the location of conn[uid].dat heap location, we can find out the value of in_ContentLength which is (0xfffffice), and the value is -800. So that means there is negative length. However, the negative length is not valid length. So negative length results in heap overflow.

```
void calloc() {
  if (size > 0) {
    void* ptr = malloc(sizeof(T) * size);
    if (ptr == NULL) {
      throw std::bad_alloc();
    }
    T* data = static_cast<T*>(ptr);
    memset(data, 0, size * sizeof(T));
    return data;
  } else {
    return nullptr;
  }
}
```
D. Taint Tracking and Data Flow analysis

Taint tracking and data flow analysis extend memory tracing and analysis the flow of data inside an application. Every memory cell and every register has an associated tag. TaintCheck [41] propose dynamic taint analysis for automatic detection of overwrite attacks, which include most types of exploits. TaintCheck doesn’t need source code or special compilation for the monitored program. DataFlowSanitizer [42] is a generalised dynamic data flow analysis. Though TaintCheck doesn’t need source code, it incur high runtime overhead. DataFlowSanitizer need source code and compiler extension to add tag information in the code. They track the whole memory while the users may just interest in sensitive memory.

E. Binary Translation

Binary translation is to instrument a binary application. For example, IR-based binary translators translate the application by using a traditional compiler approach. It can add the desired instrumentation and generates machine code for the desired instrumentation, such as DynamoRIO [43], PIN [27], QEMU [44], and Valgrind [9]. Instrumentation will incur more performance overhead. Meanwhile, it is no easy for user to choose user-defined sensitive memory. Selfie can provide much more feasible for users.

F. Memory Analysis and Recovery

Reviver [45] proposes one memory data structure instance recovery framework to analyze the memory layout. [46] makes one memory data attack once learning about the memory layout. Discrete [47] provides memory rendering through reuse of application logic to reverse engineer a memory image for more semantic information. Discrete heavily relies on exact identification of the so-called P function within the binary that takes as input the target data structure instance and produce the human readable application output. Discrete tries to figure out which memory is useful and to recover. However, Selfie can provide the user-defined sensitive memory and narrow the range of recovery.

X. Conclusion

Different users always have different requirement for sensitive memory definition. It is not flexible for aborting program execution once detecting memory corruption. Because the users may loose some sensitive data. We presented Selfie, a hybrid solution to provide one flexible solution to protect the sensitive memory according to users’ requirements in runtime. In addition, Selfie provides one comprehensive solution to detect the heap memory corruptions and figure out the root cause of memory corruption by data structure extracting and dynamic program slicing. Further, Selfie will decide whether the execution recovery is necessary.

REFERENCES

[1] J. P. Anderson, “Computer security technology planning study, volume 2,” DTIC Document, Tech. Rep., 1972.
[2] C. Xiaobo, S. Mike, and C. Dan, “New zero-day exploit targeting internet explorer versions 9 through 11 identified in targeted attacks,” 2014.
[3] L. Szekeres, M. Payer, T. Wei, and D. Song, “Sok: Eternal war in memory,” in Security and Privacy (SP), 2013 IEEE Symposium on. IEEE, 2013, pp. 48–62.
[4] A. One, “Smashing the stack for fun and profit,” Phrrack magazine, vol. 7, no. 49, pp. 14–16, 1996.
[5] H. Shacham, “The geometry of innocent flesh on the bone: Return-into-libc without function calls (on the x86),” in Proceedings of the 14th ACM conference on Computer and communications security. ACM, 2007, pp. 552–561.
[6] T. M. Austin, S. E. Breach, and G. S. Sohi, Efficient detection of all pointer and array access errors. ACM, 1994, vol. 29, no. 6.
[7] S. H. Yong and S. Horwitz, “Protecting c programs from attacks via invalid pointer dereferences,” in ACM SIGSOFT Software Engineering Notes, vol. 28, no. 5. ACM, 2003, pp. 307–316.
[8] D. Avots, M. Dalton, V. B. Livshits, and M. S. Lam, “Improving software security with a c pointer analysis,” in Proceedings of the 27th international conference on Software engineering. ACM, 2005, pp. 332–341.
[9] N. Nethercote and J. Fitzhardinge, “Bounds-checking entire programs without recompiling,” SPACE, 2004.
[10] E. D. Berger and B. G. Zorn, “Diehard: probabilistic memory safety for unsafe languages,” in ACM SIGPLAN Notices, vol. 41, no. 6. ACM, 2006, pp. 158–168.
[11] 2015, CVE-2015-0235: GHOST: glibc gethostbyname buffer overflow; available at https://www.qualys.com/2015/01/27/cve-2015-0235/GHOST-CVE-2015-0235.txt.
[12] 2015, what is a “good” memory corruption vulnerability?; available at http://googleprojectzero.blogspot.com/2015/06/what-is-good-memory-corruption.html.
[13] D. Vogt, C. Giaffrida, H. Bos, and A. S. Tanenbaum, “Lightweight memory checkpointing,” in Dependable Systems and Networks (DSN), 2015 45th Annual IEEE/IFIP International Conference on. IEEE, 2015, pp. 474–484.
[14] M. Conover, “w00w00 on heap overflows,” 1999.
[15] W. K. Robertson, C. Kruegel, D. Mutz, and F. Valeur, “Run-time detection of heap-based overflows.” in JISA, vol. 3, 2003, pp. 51–60.
[16] E. D. Berger, “Heapshield: Library-based heap overflow protection for free,” UMass CS TR, pp. 06–28, 2006.
[17] A. Krennmaier, “Contrapollce: a libc extension for protecting applications from heap-smashing attacks,” 2003.
[18] Q. Zeng, D. Wu, and P. Liu, “Cruiser: concurrent heap buffer overflow monitoring using lock-free data structures,” ACM SIGPLAN Notices, vol. 46, no. 6. pp. 367–377, 2011.
[19] M. Bauer, S. Treichler, E. Slaughter, and A. Aiken, “Structure slicing: Extending logical regions with fields,” in Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis. IEEE Press, 2014, pp. 845–856.
[20] C. Lattner, “Llvm and clang: Next generation compiler technology,” in The BSD Conference, 2008, pp. 1–2.
[21] 2015, bear toolset; available at https://github.com/rizsotto/Bear.
[22] H. Agrawal and J. R. Horgan, “Dynamic program slicing,” in ACM SIGPLAN Notices, vol. 25, no. 6. ACM, 1990, pp. 246–256.
[23] A. Zavou, G. Portokalidis, and A. D. Keromytis, “Self-healing multitier applications using cascading rescue points,” in Proceedings of the 28th Annual Computer Security Applications Conference. ACM, 2012, pp. 379–388.
[24] F. Qin, J. Tucek, J. Sundaresan, and Y. Zhou, “Rx: treating bugs as allergies—a safe method to survive software failures,” in ACM SIGOPS Operating Systems Review, vol. 39, no. 5. ACM, 2005, pp. 235–248.
[25] Q. Gao, W. Zhang, Y. Tang, and F. Qin, “First-aid: surviving and preventing memory management bugs during production runs,” in Proceedings of the 4th ACM European conference on Computer systems. ACM, 2009, pp. 159–172.
[26] 2015, libhijack: Runtime Process Infection; available at https://github.com/SoldierX/libhijack.
[27] C.-K. Luk, R. Cohn, R. Muth, H. Patil, A. Klausner, G. Lowney, S. Wallace, V. J. Reddi, and K. Hazelwood, “Pin: building customized
program analysis tools with dynamic instrumentation,” in ACM Sigplan Notices, vol. 40, no. 6. ACM, 2005, pp. 190–200.

[28] 2015, triton: A Pin-based dynamic symbolic execution (DSE) framework; available at http://triton.quarkslab.com/.

[29] 2013, enhancing Giri: Dynamic Slicing in LLVM; available at https://github.com/iiuml07/giri.

[30] 2002, remote exploitable heap overflow in Null HTTPd 0.5.0; available at http://archive.cert.uni-stuttgart.de/bugtraq/2002/09/msg00269.html.

[31] E. Bugnion, V. Chipounov, and G. Candea, “Lightweight snapshots and system-level backtracking,” in Proceedings of the 14th Workshop on Hot Topics in Operating Systems, no. EPFL-CONF-185945. USENIX, 2013.

[32] J. F. Ruscin, M. Heffner, S. Varadaranjan et al., “Dejavu: Transparent user-level checkpointing, migration, and recovery for distributed systems,” in Parallel and Distributed Processing Symposium, 2007. IPDPS 2007. IEEE International. IEEE, 2007, pp. 1–10.

[33] Y. Li and Z. Lan, “Frem: a fast restart mechanism for general checkpoint/restart,” Computers, IEEE Transactions on, vol. 60, no. 5, pp. 639–652, 2011.

[34] A. Lenharth, V. S. Adve, and S. T. King, “Recovery domains: an organizing principle for recoverable operating systems,” in ACM SIGARCH Computer Architecture News, vol. 37, no. 1. ACM, 2009, pp. 49–60.

[35] G. Portokalidis and A. D. Keromytis, “Reassure: A self-contained mechanism for healing software using rescue points,” in Advances in Information and Computer Security. Springer, 2011, pp. 16–32.

[36] K. Pattabiraman, V. Grover, and B. G. Zorn, “Samurai: protecting critical data in unsafe languages,” in ACM SIGOPS Operating Systems Review, vol. 42, no. 4. ACM, 2008, pp. 219–232.

[37] M. Payer, E. Kravina, and T. R. Gross, “Lightweight memory tracing.” in USENIX Annual Technical Conference, 2013, pp. 115–126.

[38] J. Marathe, F. Mueller, T. Mohan, S. A. Mckee, B. R. De Supinski, and A. Yoo, “Metric: Memory tracing via dynamic binary rewriting to identify cache inefficiencies,” ACM Transactions on Programming Languages and Systems (TOPLAS), vol. 29, no. 2, p. 12, 2007.

[39] P. Sun, “Exploring semantic reverse engineering for software binary protection,” in Proceedings of School of Graduate Studies Electronic Theses and Dissertations. Rutgers University, 2019.

[40] S. Zonouz, M. Zhang, P. Sun, L. Garcia, and X. Liu, “Dynamic memory protection via intel sgx-supported heap allocation,” in 2018 IEEE 16th Intl Conf on Dependable, Autonomic and Secure Computing, 16th Intl Conf on Pervasive Intelligence and Computing, 4th Intl Conf on Big Data Intelligence and Computing and Cyber Science and Technology Congress (DASC/PICOM/DataCom/CyberSciTech). IEEE, 2018, pp. 608–617.

[41] J. Newsome and D. Song, “Dynamic taint analysis for automatic detection, analysis, and signature generation of exploits on commodity software.” 2005.

[42] Clang DataFlowSanitizer; available at http://clang.llvm.org/docs/DataFlowSanitizer.html.

[43] D. Brueining, T. Garnett, and S. Amarasinghe, “An infrastructure for adaptive dynamic optimization,” in Code Generation and Optimization, 2003. CGO 2003. International Symposium on. IEEE, 2003, pp. 265–275.

[44] F. Bellard, “Qemu, a fast and portable dynamic translator” in USENIX Annual Technical Conference, FREENIX Track, 2005, pp. 41–46.

[45] P. Sun, R. Han, M. Zhang, and S. Zonouz, “Trace-free memory data structure forensics via past inference and future speculations,” in Proceedings of the 32nd Annual Conference on Computer Security Applications. ACM, 2016, pp. 570–582.

[46] D. Shelar, P. Sun, S. Amin, and S. Zonouz, “Compromising security of economic dispatch in power system operations,” in 2017 47th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN). IEEE, 2017, pp. 531–542.

[47] B. Saltarformaggio, Z. Gu, X. Zhang, and D. Xu, “Discrete: automatic rendering of forensic information from memory images via application logic reuse,” in Proceedings of the 23rd USENIX conference on Security Symposium. USENIX Association, 2014, pp. 255–269.
Fig. 3: Function Call Graph for NullHTTPD