

Memory Forensics Techniques for Automated Detection and Analysis of Go Malware

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ARTICLE INFO

Keywords:

Go
Golang
Malware
Memory Forensics
Volatility 3

ABSTRACT

The Go programming language has become increasingly popular among malware developers due to its ability to produce statically linked, cross-platform executables that challenge traditional analysis techniques. These binaries embed a substantial runtime and compiler-generated metadata and are compiled with aggressive optimizations that discard type information for function parameters and local variables. Go's design further complicates analysis by representing strings as pointer-length pairs rather than null-terminated sequences, employing a caller-allocated stack model that obscures argument boundaries, and fragmenting program state across concurrent goroutines. Although existing static analysis and reverse engineering tools provide Go-specific support, they remain limited to compile-time artifacts and cannot recover runtime execution state and artifacts that persist solely in memory. To address this gap, we present the first memory forensics framework for runtime analysis of Go binaries. By parsing Go's internal structures, our framework reconstructs type and function metadata, recovers heap-allocated and static strings, and distinguishes application-level functions. Through ABI-aware backward analysis, it derives execution paths and argument values from call sites. To capture runtime state beyond what static analysis reveals, it analyzes goroutine stacks to identify actively executing functions and recover their runtime argument values. We implemented all capabilities as Volatility 3 plugins and evaluated them against malware observed in recent incidents, such as the *BRICKSTORM* backdoor, *Obscura* ransomware, and *Pantegana* RAT, as well as open-source samples for reproducibility. The framework successfully recovered C2 endpoints, persistence mechanisms, encryption keys, ransom notes, and execution state, including critical runtime artifacts that were absent from published threat intelligence.

1. Introduction

The Go programming language has become increasingly popular among malware authors due to its cross-platform compilation capabilities, which allow a single codebase to produce executables targeting multiple platforms (Grunzweig, 2019, Maurya, 2021, Stevens, 2025). This adoption has created significant challenges for malware analysts and incident responders. Go produces statically linked binaries that embed a substantial custom runtime and extensive compiler-generated metadata, resulting in large executables (d4rkssystem, 2025). Moreover, such binaries are compiled with aggressive optimizations that discard type information for function parameters and local variables (InstaTunnel Team, 2025). These properties reduce the effectiveness of traditional detection mechanisms and complicate reverse engineering.

Go's design introduces further obstacles for analysis. Unlike C and C++, strings are represented as pointer-length pairs rather than null-terminated byte sequences, eliminating explicit delimiters and thus making reliable extraction of string-based artifacts difficult (Guerrero-Saade, 2021). Dynamic analysis is similarly challenging, as Go employs a caller-allocated stack model in which arguments and return values reside in caller-reserved memory regions, obscuring argument boundaries and complicating parameter recovery

(Calvet, 2019). These inherent challenges are compounded when binaries are stripped of symbols, lack debug information, or are obfuscated using tools such as Garble, which hashes identifiers and removes metadata to disrupt static analysis (Raimbaud and Rascagneres, 2025).

Although reverse-engineering tools, including *IDA Pro* and *Ghidra*, have improved their support for Go binaries (Hex-Rays, 2025, Trellix, 2023), they rely on heuristic-based disassembly without fully parsing the embedded metadata. This results in incomplete function boundaries, fragmented call graphs, and prototypes lacking type annotations. Specialized tools, such as *GoReSym*, address these limitations by parsing metadata structures derived from the Go runtime source code (Mandiant, 2026, Stephen Eckels). Nevertheless, all existing tools remain limited to compile-time artifacts and cannot reconstruct runtime program state or recover critical runtime artifacts that reside solely in memory, such as decrypted strings, encryption keys, and command-and-control configurations.

To address this gap, this paper introduces the first memory forensics framework for runtime analysis of Go binaries. By parsing Go's internal structures, including `pcIntab` and `moduledata`, it recovers function metadata, type descriptors, and interface tables. Leveraging this metadata, the framework identifies heap objects, extracts dynamically allocated and static strings, and classifies functions by origin. Through ABI-aware backward analysis, it derives execution paths and argument values from call sites. Goroutine stack analysis extends this to runtime state, identifying actively executing

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functions and recovering argument values that exist only at execution time. By relying on structural validation rather than symbolic information, the framework remains effective on stripped binaries and maintains robustness against obfuscation that corrupts version identifiers and magic bytes within `pcIntab`.

We implemented our framework as a suite of Volatility 3 plugins (Volatility Foundation, 2025), supporting multiple Go versions on both Linux and Windows. We evaluated it against real-world malware recently observed in the wild, including the *BRICKSTORM* backdoor (Cybersecurity and Infrastructure Security Agency (CISA) et al., 2025, Mandiant, 2025a), *Pantegana* RAT (Hunt.io, 2025b,a), *Obscura* ransomware (Carvey et al., 2025, Coveware by Veeam, 2025), as well as the open-source *Screenshotter* application for reproducibility (omaidf, 2025). Results demonstrate that `go_strings` successfully extracted string artifacts with clear boundaries and memory locations, such as hard-coded credentials from *Screenshotter*, which appear only as concatenated data in standard strings output. From *Obscura*, it recovered the ransom note, Curve25519 public key, and threat actor communication channels, including a *Tor* hidden service URL and *TOX* messaging ID. The `go_functions` plugin recovered complete binary paths and classified functions by source file, while its ABI-aware backward analysis of *BRICKSTORM* revealed C2 endpoints, persistence paths, and DNS-over-HTTPS resolver settings. Finally, `go_goroutines` analyzed *Pantegana* goroutine stacks, recovering deployment-specific C2 configuration from active function arguments, such as server address, API endpoints, and beacon intervals. We summarize the contributions of this paper as follows:

- We present the first memory forensics framework for reconstructing the runtime behavior of Go binaries, enabling analysis beyond compile-time artifacts.
- We parse Go's internal structures to extract strings from heap and static sections, classify functions by origin, derive execution paths and argument values, and analyze goroutine stack to recover execution state.
- We implement the proposed framework as Volatility 3 plugins and evaluate it on real-world Go malware, demonstrating accurate recovery of critical runtime forensic artifacts.

The paper is organized as follows. Section 2 summarizes related work. Section 3 explains the framework. Section 4 presents the evaluation, Section 5 discusses limitations and future directions, and Section 6 concludes the paper.

2. Related Work

Prior work has shown that malware frequently abuses userland runtimes, motivating memory forensics techniques that reconstruct high-level execution state from process memory. The Android runtime, for example, has been widely targeted to access sensitive resources, such as call history, text messages, microphones, and cameras (Smmarwar et al., 2024). In response, multiple memory analysis approaches have been proposed to acquire Android memory and detect

runtime-resident malicious behavior (Sylve et al., 2012, Case and Richard III, 2017, Ali-Gombe et al., 2020, 2019, Tam et al., 2015). On macOS, the Objective-C and Swift runtimes have similarly been analyzed using Volatility plugins to detect suspicious method invocation, keystroke logging, and runtime manipulation (Case and Richard III, 2016). Subsequent research extended these capabilities to enumerate loaded classes and instances, decode type information, and identify suspicious API usage and malicious function calls (Manna et al., 2021). The .NET and .NET Core runtimes have also been subject to analysis that extract memory-resident assemblies and recover runtime components, such as classes, fields, methods, and native imports (Manna et al., 2022). More recently, researchers analyzed the V8 JavaScript runtime by extracting and tracing V8 objects via internal structures such as *MetaMap* (Wang et al., 2022), and analyzed the Python runtime by recovering modules, classes, functions, and execution context to capture malicious behavior (Ali et al., 2025b,a).

3. Memory Analysis Framework

This section presents our memory forensics framework, which recovers Go's embedded runtime metadata as the foundation for all subsequent analysis.

3.1. Go Runtime Metadata Extraction

Go binaries embed linker-generated metadata that supports core runtime functionality, including stack unwinding and garbage collection. A primary component of this metadata is `pcIntab` (program counter line table), which begins with a `pcHeader` structure. The `pcHeader` contains version-identifying magic bytes, architectural parameters, such as the minimum instruction size (`minLC`) and pointer size (`ptrSize`), counts of functions and source files (`nfunc`, `nfiles`), and relative offsets to several internal tables. These tables include `funcnametab`, which stores function name strings; `filetab`, which stores source file paths; `cutab`, which maps compilation units to ranges of file indices; `pctab`, which encodes PC-value data used for stack frame size and line number resolution; and `pcIntable`, which contains the function table (`ftab`) and associated `_func` structures. Each `ftab` entry maps a function's entry program counter to its corresponding `_func` structure, which references the function name, PC-value streams, and source file information.

When a Go binary is loaded, the runtime initializes `moduledata`, a linker-emitted structure located in a writable data section. This structure references the same internal tables as `pcHeader`, but uses absolute addresses resolved at process initialization rather than relative offsets. In addition, `moduledata` defines memory region boundaries for the loaded binary, including `text`, `data`, `bss`, `rodata`, and `types`. It also contains two slice fields: `typelinks`, which store offsets to type descriptors, and `itablinks`, which store pointers to interface tables (`itab`) that bind concrete types with implemented interfaces. Figure 1 summarizes the metadata extraction pipeline. The primary path recovers metadata from process memory, while a supplementary path extracts paged-out function names and source file paths from the cached binary.

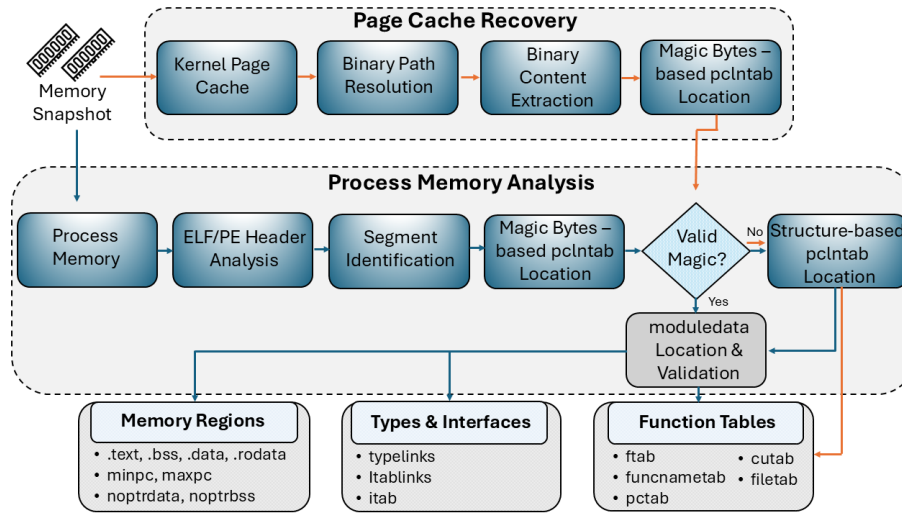


Figure 1: Go runtime metadata extraction

3.1.1. Process Memory Analysis

The framework parses the executable header to identify program segments and then scans read-only segments for `pcIntab` using version-specific magic bytes: `\xf1\xff\xff\xff` (Go 1.20+), `\xf0\xff\xff\xff` (Go 1.18–1.19), `\xfa\xff\xff\xff` (Go 1.16–1.17), and `\xfb\xff\xff\xff` (Go 1.2–1.15). Each candidate match is validated by enforcing `pcHeader` invariants, requiring zeroed padding bytes, $\text{minLC} \in \{1, 2, 4\}$, $\text{ptrSize} \in \{4, 8\}$, and function and file counts within reasonable bounds. When magic-byte detection fails due to obfuscation, the framework transitions to structure-based discovery, evaluating aligned addresses using these same invariants. Once `pcIntab` is validated, the framework locates `moduledata` by scanning writable segments for a pointer equal to the recovered `pcHeader` address, as the first field of `moduledata` references `pcHeader`. Candidate structures are then validated by enforcing ordered memory regions (e.g., `data < edata`) and well-formed slice headers satisfying $\text{len} \leq \text{cap}$.

3.1.2. Page Cache Recovery

Function names and source file paths are primarily used for diagnostics (i.e., panic messages and stack traces) and are rarely accessed during normal execution, as the runtime operates directly on program counters. Consequently, pages containing `funcnametab` entries may be paged out under memory pressure, particularly for infrequently executed code. To recover complete metadata, the framework additionally extracts `pcIntab` from the kernel page cache. In ELF binaries, `pcIntab` resides in the `.gopcIntab` section, and, in PE binaries, it is embedded as the `runtime.symtab` symbol within the `.symtab` section. In contrast, `moduledata` cannot be reconstructed from page cache alone, as it is only partially initialized in the static binary and is finalized by the runtime during process startup.

3.1.3. Obfuscation Handling

Go obfuscation tools, such as *Garble*, explicitly target symbolic and metadata-level artifacts (Martí, 2024), including function names, file paths, type names, and static strings,

to hinder static analysis and reverse engineering. These transformations do not modify the core components required by the Go runtime for correct execution. Accordingly, our framework avoids reliance on symbolic information and instead analyzes runtime structures directly, as discussed earlier in this section. Heap spans and goroutine objects are recovered based on their structural layout rather than by resolving the `runtime.mheap` or `runtime.allgs` symbols. Consequently, recovery of critical forensic artifacts, such as function bodies, argument layouts, type descriptors, heap objects, and goroutine stacks, remains robust under obfuscation. In addition, dynamically allocated strings located in the heap remain in plaintext at runtime and are therefore unaffected by compile-time obfuscation, representing a key advantage of memory forensics over static analysis.

Given that obfuscation can corrupt or randomize version identifiers and magic bytes within the `pcIntab`, our framework identifies the Go version based on changes in data structures introduced across Go releases. For example, the `textStart` field in `pcHeader`, as well as the `rodata` and `gofunc` fields in `moduledata`, are introduced in Go 1.18. Coverage-related fields (`covctrs`, `ecovctrs`) and the `inittasks` field appear in Go 1.20, while the `sys.NotInHeap` marker is introduced in Go 1.21. However, when symbolic deobfuscation is required, existing tools can be applied to executables extracted from memory. For example, *GoReSym* (Mandiant, 2026) reconstructs function and package symbols using Go runtime metadata and heuristic analysis; *GoStringUngarble* (Mandiant, 2025b) recovers strings obfuscated by *Garble*; and *GoResolver* (Volety, 2025) resolves obfuscated standard library functions via control-flow graph similarity.

3.1.4. Type Metadata Extraction

Each entry in `typelinks` references a type descriptor beginning with a common `_type` header, which encodes size, pointer metadata (`ptrdata`), alignment requirements (`align`, `fieldAlign`), type flags (`tflag`), and a type kind (`kind`). Go defines 26 kinds spanning primitive, composite, and abstract

types (Calvet, 2019). Following the common header, descriptors include kind-specific metadata sufficient to traverse and reconstruct typed values, such as pointers, slices, arrays, structs, interfaces, functions, and methods. For type methods, the descriptor is further followed by an `uncommonType` structure containing method-related metadata, including the package path, method counts, and references to method descriptors. Each method descriptor specifies the method name, the number of input parameters and return values, the concrete types of each, and the entry points for direct (`tfn`) and interface-based (`ifn`) invocation.

3.1.5. Interface Metadata Extraction

Each `itab` entry stores pointers to interface type descriptor (`inter`), concrete type descriptor (`_type`), cached type hash, and function pointer array (`fun`) used for method dispatch. The `fun` array contains one entry per interface method, ordered according to the interface's method set, with each entry holding the program counter of the concrete implementation. We parse each `itab` by resolving `inter` to recover the interface method set and `_type` to identify the implementing type. The `fun` entries then provide direct mappings from interface methods to concrete implementations, enabling resolution of polymorphic calls executed via interface dispatch.

3.2. String Recovery

Go represents strings as a structure comprising a pointer to the underlying UTF-8 byte array and an integer specifying the length. This separates headers from backing data, with each potentially residing in different memory regions. For instance, heap-resident and stack-resident headers reference data in either the heap (for dynamically created strings) or `.rodata` (for static constants). In contrast, headers in static sections (`.rodata`, `.data`, `.bss`) always reference data located only in `.rodata`, as these represent compile-time literals or global variables initialized with constant strings.

3.2.1. Heap-Based String Recovery

Recovering heap-resident strings requires identifying allocated heap objects and interpreting them using runtime type metadata. Figure 2 summarizes this process.

Heap Structure Parsing. The Go heap is organized into spans containing fixed-size slots for objects of a given size class. While span recovery relies on locating the global `runtime.mheap` symbol, this structure is large, vary across versions, and may be absent in stripped or obfuscated binaries. Instead, we locate the `allspans` slice header within the `.data` or `.bss` sections and validate candidates using alignment checks, length–capacity constraints, and verification that referenced entries point to valid `mspan` structures. Each `mspan` describes a contiguous memory region divided into fixed-size slots. Key fields include the base address (`startAddr`), slot size (`elemsize`), total capacity (`nelems`), number of allocated objects (`allocCount`), allocation bitmap (`allocBits`), and span state. For active spans, allocated objects are recovered by iterating the allocation bitmap and calculating object addresses using their `bit_index` (position in the bitmap).

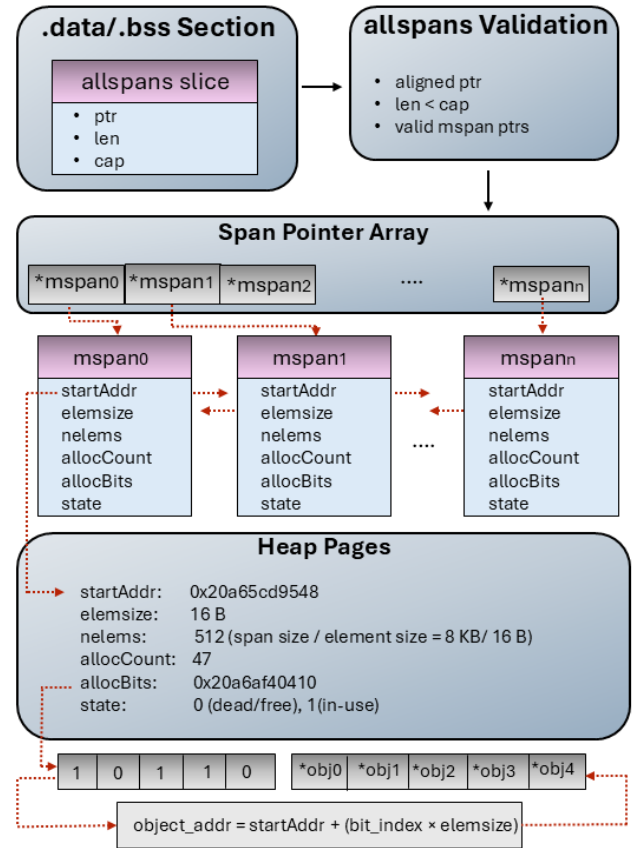


Figure 2: Heap object recovery

Size-to-Type Mapping. Heap objects lack type annotations, preventing direct identification of their types. We therefore infer candidate types by correlating the object size specified by each span's `elemsize` with recovered type descriptors. By extracting `_type.size` from each descriptor, we group types by size and map heap object sizes to candidate types. Since multiple types may share the same size, a single object size may correspond to several candidates. To reduce ambiguity, candidates are restricted to types whose layout may directly contain or indirectly reference string values. These include strings; arrays or slices of strings; composite types that reference string-typed elements or fields; maps whose key or value type involves strings; and interfaces, whose concrete types are determined dynamically at runtime and therefore cannot be excluded statically.

Type-Guided Object Interpretation. After identifying candidate types for each object, we interpret the object under each candidate type. For objects whose size equals two machine words, we first disambiguate interface and string representations. If the first word points to a valid `itab` address, the object is treated as an interface value and its concrete payload is processed recursively. Otherwise, we treat the first word as a potential string data pointer and the second as a potential length. We then validate that the pointer references accessible memory, the length is within reasonable bounds, and the referenced bytes form valid UTF-8 with predominantly printable characters. Objects that fail string validation are excluded and evaluated under the

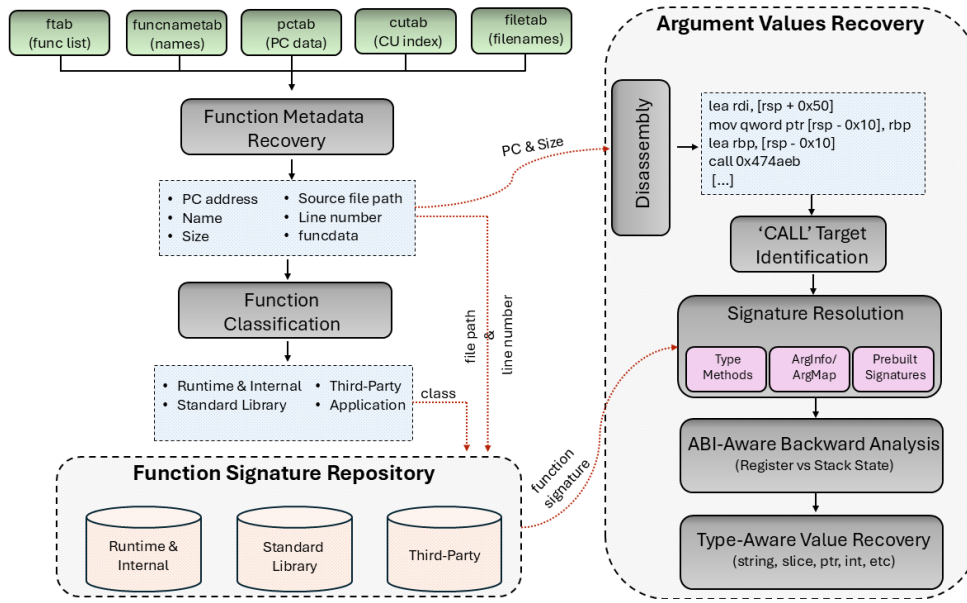


Figure 3: Function analysis workflow

remaining candidates. Pointer-typed objects, slices, structures, and maps (hash tables) are analyzed using the same algorithm against their contained fields.

3.2.2. Static Section String Recovery

Unlike the heap, static sections (.rodata, .data, and .bss) store data sequentially without size metadata or explicit object boundaries. To recover strings from these regions, we scan for patterns matching Go string headers. For each aligned candidate, the first word is interpreted as a potential data pointer and the second as a potential length, and candidates are validated using the same pointer, length, and content checks described earlier. This pattern-based approach enables recovery of compile-time string literals and global string variables that reference constant data.

3.3. Function Analysis

Figure 3 illustrates the function analysis workflow to recover function metadata, classify functions by origin, infer argument types, and apply ABI-aware backward analysis to recover argument values at call sites.

3.3.1. Function Metadata Recovery

We recover function metadata by parsing the internal tables referenced by moduledata (Section 3.1). Each function is described by a `_func` structure, which references the function name via `nameoff` (an offset into `funcnametab`), identifies its compilation unit via `cuOffset`, and provides offsets into PC-relative metadata streams in `pctab` for stack frame sizes (`pcsp`), source file indices (`pcfile`), and line numbers (`pc1n`). These streams encode metadata as compact sequences of value and program-counter deltas, allowing metadata to be resolved at arbitrary instruction addresses within the function. Although a function is defined in a single source file, inlined and compiler-generated code may originate from other files. Consequently, source file paths are not stored directly in `_func`. Instead, the file index is decoded from the `pcfile` stream at the target program counter and combined

with `cuOffset` to index into `cutab`, yielding the corresponding offset into `filetab` where the source file path resides.

3.3.2. Function Classification

Once the source file path is recovered, we use it to classify functions. Paths beginning with `runtime/` are classified as runtime core, while paths under `internal/` are split into runtime-critical internal packages (e.g., `internal/abi`, `internal/cpu`) and other standard-library internal packages (e.g., `internal/poll`). Paths whose first segment matches a public standard library package (e.g., `net`, `os`, `fmt`) are classified as public standard library. On the other hand, third-party functions are identified by domain-based prefixes (e.g., `github.com`, `gitlab.com`) or by paths under `vendor/` directories. Remaining functions, including those in the `main` package and other user-defined packages within the same module, are classified as application-level code.

3.3.3. Argument Type Inference

We leverage the recovered source file path and entry line number to resolve function identities via signature repositories, particularly when function names are unavailable due to paging. Each signature associates a function name with its defining file, entry line number, and parameter types. For type methods, signatures are recovered directly from the `uncommonType` structure. For runtime, internal, and standard library functions, we parse the official Go source distribution for the detected Go version, extracting signatures from both `.go` source files and compiler-generated `.s` assembly files. For third-party dependencies, which vary across applications, signatures are generated on demand by parsing the corresponding source packages.

Application-level functions present a distinct challenge as their signatures are not known a priori and type information is frequently eliminated by aggressive compiler optimizations. To address this, we infer argument structure from

compiler-generated metadata stored in the `funcdata` associated with each `_func`. For binaries compiled with Go 1.17 and later, we parse `ArgInfo` bytecode, while for earlier versions we rely on `ArgsPointerMaps`. Both structures describe the layout of arguments within the call frame. `ArgInfo` encodes argument boundaries explicitly, representing scalar arguments by their frame offsets and sizes, and composite arguments (e.g., strings, slices, structs) as aggregates delimited by start and end markers. Unlike `ArgInfo`, `ArgsPointerMaps` encodes only a bitmap indicating which stack slots within the argument area contain pointers, without explicit argument boundaries. We therefore infer boundaries using Go's type layout conventions.

3.3.4. ABI-Aware Backward Analysis

Once signatures are resolved, we map parameters to their locations based on the calling convention. Go 1.17 and later use a register-based ABI, passing arguments through general-purpose registers and spilling excess arguments to the stack (The Go Authors, 2024). Earlier versions use a stack-based ABI, placing all arguments at consecutive word-aligned stack offsets. To recover argument values, we disassemble the caller function and traverse backward from each `CALL` instruction to identify the last write to each argument location. Immediate `mov` instructions define constant values, register-to-register `mov` instructions propagate values through copy chains, `RIP`-relative `leaq` instructions compute addresses of static data, and `xor reg, reg` patterns indicate zero initialization. Traversal terminates at preceding call instructions to avoid crossing call boundaries, as register contents may be modified by callees.

3.4. Goroutine Stack Analysis

Go maintains a global slice, `runtime.allgs`, containing pointers to all goroutine structures. As stripped binaries lack this symbol, we scan writable memory regions for candidate slice headers and validate them by ensuring that the referenced array contains pointers to well-formed `g` structures. A candidate `g` is considered valid if its stack bounds are properly aligned and ordered, its status field encodes a correct runtime state, and its goroutine identifier falls within reasonable bounds.

Stack Unwinding. Each goroutine's execution state is stored in the `g.sched` field, which stores the current stack pointer (`sp`) and program counter (`pc`). We reconstruct the call stack by iteratively unwinding frames starting from these values. At each iteration, the corresponding function is identified by searching the function table (`ftab`) for the entry whose PC range encompasses the current `pc`. The `pcsp` stream of the function is then decoded to obtain `sp_delta`, representing the frame size at that `pc`. Adding `sp_delta` to the current `sp` locates the caller's return address, which resides at the boundary between frames. Since Go's calling convention places callee arguments in caller-allocated stack space (The Go Authors, 2024), the argument area begins immediately above the return address at `sp + sp_delta + ptrSize`, where `ptrSize` denotes the pointer size. To advance to the caller's frame, the return address becomes the new `pc` and the

argument base becomes the new `sp`. Unwinding continues until an invalid return address is encountered or the stack bounds are exceeded. Once the argument base is determined, individual argument boundaries are established using the argument type reference techniques described in Section 3.3.

4. Experimental Evaluation

We implemented our framework as a suite of Volatility 3 plugins, namely `go_strings`, `go_functions`, and `go_goroutines`, and evaluated them using memory images collected from controlled executions of precompiled Go binaries¹. Page cache recovery leveraged existing Volatility 3 plugins, `linux.pagecache` and `windows.dmpfiles`, while function disassembly was performed using *Capstone* (Capstone Engine Team, 2024). Our evaluation includes Linux memory images of the *BRICKSTORM* backdoor (Go 1.16.3) and *Pantegana* RAT (Go 1.25.5), a Windows memory image of the *Obscura* ransomware (Go 1.15), and an open-source *Screenshotter* application compiled with Go 1.24.10.

4.1. Screenshotter Memory Analysis

We demonstrate the advantages of `go_strings` over the standard `strings` utility on the *Screenshotter* sample. In statically linked Go binaries, compile-time string literals are stored as contiguous blobs without null terminators. These blobs combine strings not only from application code, but also from the Go runtime and third-party libraries. As a result, `strings` produces a single concatenated output stream from which individual artifacts are difficult to recover. As shown in Figure 4a, application-specific artifacts, including the username, password, and remote host used for SFTP-based screenshot exfiltration, are indistinguishable within the output. In contrast, Figure 4b shows that `go_strings` reconstructs Go string headers together with their backing data and memory locations. This enables reliable extraction of sensitive forensic artifacts and identifies whether strings are compile-time constants or generated at runtime.

4.2. Obscura Ransomware Memory Analysis

Obscura is a Go-based ransomware first observed in August 2025, targeting enterprise environments through domain controller compromise and `NETLOGON` share distribution (Carvey et al., 2025). It employs XChaCha20 encryption with Curve25519 key agreement, terminates security software prior to encryption, and deletes volume shadow copies to prevent recovery. We analyzed a memory image from an infected Windows host containing a live *Obscura* process (PID 1100). Using `go_strings`, we reconstructed heap allocation state (112 of 942 spans active) and recovered 778 strings from 550 heap objects, along with 728 additional strings from non-heap regions. Table 1 presents runtime artifacts recovered from memory, compared against public threat intelligence reports on *Obscura* (Carvey et al., 2025, Meskauskas, 2025). Highlighted entries denote artifacts absent from these reports: the 32-byte Curve25519 public key

¹The plugins are available at <https://github.com/HalaAli198/Go-Memory-Forensics>.

```

user1@ubuntu:~/go_malware/Screenshotter$ strings -a screenshotter | grep -E "username|user1password|192.168.181.138"

writetofips140SHA-224SHA-256SHA-384SHA-512Ed25519MD5-RSAavx512fos/execrunmetls3desanswersAES-CBCusernameGoStringThursday
SaturdayFebruaryNovemberDecember%!Month(3des-cbcpasswordhostkeynistp256nistp384nistp521runtime:sp=abimismatchwrongtimersil
legalseekinvalidslothostisdownmultipathtcp127.0.0.1:53nosuchhostunknownportinvalidportinvalidbaseECDSA-SHA256ECDSA-SHA384E
CDSA-SHA512randautoseednotpollablegotypesaliashttmuxgo121tlsunsafeekmRCodeSuccessRCodeRefused/dev/urandomunknown
sizeuser1password/etc/zoneinfoistoolargenoconnectionSSH_FXP_CLOSESSH_FXP_WRITESSH_FXP_LSTATSSH_FXP_FSTATSSH_FXP_MKDIRSSH_F
XP_RMDIRSSH_FXP_ATTRSSH_FXP_SFTP:%q(%v)hmac-sha2-256hmac-sha2-512filtermethodButtonPresscrypto/fips140mime/multipartRCodeNameErro
rResourceHeaderunknownbyte192.168.181.138,M3.2.0,M11.1.0packetoolongconnectionlostSSH_FXP_VERSIONSSH_FXP_SETSTATSSH_FXP_
OPENDIRSSH_FXP_READDIRSSH_FXP_SYMLINKssh

```

(a) Concatenated output produced by the Linux strings utility

```

user1@ubuntu:~/volatility3$ python3 vol.py -f /mnt/hgfs/Screenshotter/Snapshot.vmem linux.go_strings.Go_Strings --pid 36796
Volatility 3 Framework 2.27.1
Struct Addr      Data Addr      Length  Value                                     Struct Location  Data Location
0xc0002ea90      0xc0002d7740    37      "Wednesday, 07-Jan-26 23:52:18 EST.png"  heap             heap
0xc0002eac0      0xc0000182a0    17      "/tmp/.X11-unix/X0"                      heap             heap
0xc0002eaf0      0xc0002d7710    37      "Wednesday, 07-Jan-26 23:34:18 EST.png"  heap             heap
[Snip]
0xc000188010     0x664706        14      "ssh-connection"                        heap             rodata
0xc000188070     0x662da8         8      "password"                              heap             rodata
0xc000188088     0x6641c4        13      "user1password"                         heap             rodata
0xc0000e4250     0xc000010390    10      "aes128-ctr"                            heap             heap
0xc00007a4f0     0xc0000103e0     9      "hmac-sha1"                             heap             heap
0xc000012040     0x664ada        15      "192.168.181.138"                      heap             rodata
[Snip]
0xc00007a560     0xc000018468    20      "umac-128@openssh.com"                 heap             heap
0xc00007a590     0xc000010410     9      "hmac-sha1"                             heap             heap
0xc000188000     0x662d60         8      "username"                              heap             rodata
0xc0001998d0     0x6f7bac        31      "image/png.(*encoder).writeImage"       heap             rodata

```

(b) Type-aware strings recovered by the go_strings plugin

Figure 4: Comparison of the go_strings plugin and the Linux strings utility

Table 1

Runtime forensic artifacts recovered from Obscura memory using go_strings. Highlighted cells indicate the novel artifacts

Artifact	Value
Curve25519 Public Key (Base64) Encryption / Key Exchange Algorithms	Z7oIV9mbFaMuePnpNBvdcweN+FiFLFVaK1a8TmVMTUs= XChaCha20 / Curve25519
TOX ID (from the note) Tor Hidden Service (from the note) Victim ID (from the note)	AE55FC0EB1C25A5B081650108F9081E236DECE1CE08D2E185A6F15B9FB48E700210BED374643 http://obscurad3aphckihv7wptdxvdn15emna6t3vikcf3c5oiinqdq6y6xad.onion 148061707215636819
Crypto Dependency System Dependency Go Toolchain (GOROOT) Path Module Path	golang.org/x/crypto v0.0.0-20201203163018-be400aefbc4c golang.org/x/sys v0.0.0-20201018230417-eeed37f84f13 /run/media/veracrypt1/Locker_Deps/go1.15.linux-amd64/go main/windows/locker
Domain Role Detection Strings	[+] detect standalone pc., [+] detect pc in domain. run transfer to dc., [+] detect BDC. run transfer to PDC., [+] detect PDC. run transfer to all pc in domain.
Runtime Status Messages	[!!!] user not admin. exit [!!!], [-] failed to delete shadow copies., [-] failed to run as daemon!, [+] encryption start. you may close this window, Error calling DsRoleGetPrimaryDomainInformation:
Security Software Antivirus	WinDefend, MsMpEng, MpCmdRun, CSFalconService, SentinelAgent bdagent, McAfee, SymCorpUI, ccSvcHst, AMService, Emsisoft*

value, which enables decryption if the corresponding private key is recovered; exact Go module dependencies revealing the cryptographic implementation, which link samples compiled from the same build environment; and the Go toolchain (GOROOT) path, which exposes the threat actor's toolchain configuration on a VeraCrypt-encrypted volume. This table also includes previously reported indicators, such as domain-role detection strings (standalone, domain member, BDC, PDC), which provide direct evidence of Obscura's propagation logic, escalating from workstations to domain controllers and subsequently targeting all domain-joined systems when executed on a primary domain controller.

Using the go_functions plugin, we recovered Obscura's functions together with their source file paths. Similar to

compiler-generated PDB paths, file paths are forensically valuable, as they expose characteristics of the build environment that may persist across malware samples (Wilhoit, 2025). In Obscura, the recovered build root (/run/media/veracrypt1/Backups/Obscura/Locker/windows/) indicates compilation from a VeraCrypt-mounted volume. Grouping recovered functions by their file paths indicates a modular internal organization. The main module (locker/locker.go) implements file discovery (scanDisk), parallel encryption (worker), ransom note deployment (dropNote), and anti-analysis checks (runtimeCheck); the encryption module (api/xchacha20.go) implements full and partial encryption routines (EncryptFull, EncryptPart); and api/api.go implements Windows API wrappers

Table 2
Recovered BRICKSTORM metadata using go_functions

Attribute	Value
Process ID (PID)	2004
Cached ELF Path	/usr/java/jre-vmware/bin/upgrademgr
ELF Architecture	64-bit, Little Endian
ELF Size (Extracted)	5,844,992 bytes
Go Version	go1.16.3hijacke
Cached Function Names	5,524
Cached File Paths	5,524
Recovered Functions	5,524
Recovered Types	3,597
Recovered Interfaces	360
Recovered Type Methods	1,695

for privilege checks (IsRunAsAdmin), drive enumeration (GetWindowsDrives), and process termination (KillProcess).

4.3. BRICKSTORM Memory Analysis

BRICKSTORM is a Go-based backdoor attributed to the China-nexus threat actor *UNC5221* and has been observed in intrusions targeting VMware vCenter infrastructure, with activity reported through December 2025 (Mandiant, 2025a, Cybersecurity and Infrastructure Security Agency (CISA), 2025). Public threat intelligence characterizes its persistence mechanisms, DNS-over-HTTPS (DoH) command-and-control, and post-exploitation capabilities, while providing limited insight into execution-time state and actionable memory-resident artifacts. We analyzed a Linux sample (PID 2004) masquerading as a VMware Java component.

Table 2 summarizes quantitative metadata recovered using the go_functions plugin, including the number of recovered functions and source file paths from both process memory and the cached binary, in addition to the number of recovered types, interfaces, and type methods.

Given that the analyzed sample was compiled with Go 1.16, argument recovery relies on parsing ArgsPointerMaps (see Section 3.3). Despite this challenge, Table 3 shows that go_functions successfully identifies *BRICKSTORM*'s main functions and execution paths and recovers argument values. We compared all recovered artifacts against the CISA malware analysis report (Cybersecurity and Infrastructure Security Agency (CISA), 2025) and Mandiant's threat intelligence publication (Mandiant, 2025a). Highlighted entries in Table 3 denote artifacts absent from those reports. These include the configuration file /etc/sysconfig/vmp (CISA documents only the parent directory /etc/sysconfig/), the KENSO and ENVLOG environment variables, the utility function wssoft/libs/utls.HasExistProc (distinct from the documented wssoft2 C2 package), raw XOR key material used to recover DoH resolver addresses (Table 4), a beacon timer interval of 0x2260ff9290000 (≈ 7 days), randomized sleep and jitter parameters (0–600 and 0–7200 seconds), the C2 termination keyword "exit", and exit code 200.

Analysis of main.startNew revealed the complete persistence workflow. The malware first checks the KENSO environment variable as a kill-switch; if set to "true", *BRICKSTORM* removes itself and terminates. Otherwise, it reads an

embedded payload from /etc/sysconfig/vmp, deletes any existing binary at /usr/java/jre-vmware/bin/upgrademgr, writes the payload with executable permissions (0755), and modifies the PATH environment variable to prioritize this directory. This masquerades the backdoor as a legitimate VMware Java Runtime component. Notably, these file paths were recovered while analyzing the main.copyFile function (Figure 5). Persistence is maintained via main.selfWatcher, which implements a watchdog that monitors process liveness and reinstalls the payload if necessary. Recovered beacon delay and jitter parameters indicate timing-based evasion, explaining *BRICKSTORM*'s resistance to sandbox analysis. Prior to C2 communication, six deobfuscation routines (main.main.func1–func6) apply bitwise XOR over stacked key arrays to recover DNS-over-HTTPS resolver endpoints. Figure 6 illustrates the XOR key pairs recovered via ABI-aware backward analysis of main.main.func1, while Table 4 enumerates the complete set of recovered keys and shows their decrypted endpoints.

4.4. Pantegana Memory Analysis

Pantegana is a fully-featured, Go-based remote access trojan that supports command execution, file transfer, and system fingerprinting. Originally released as an open-source project, it was later abused by the China-nexus group Red-November in a global espionage campaign targeting government ministries, defense contractors, and critical infrastructure, after which the repository was removed from GitHub (Hunt.io, 2025b,a). To conduct our experiment, we obtained a preserved copy of the original source code, compiled the client and server following the same configuration reported in prior analyses, and executed *Pantegana* within a controlled local network environment. We captured memory from the "victim" system after executing several reconnaissance commands from the server. We then used go_functions to reconstruct the execution flow that starts at main.main and proceeds to client.RunClient, which orchestrates the RAT's core functionality by calling client.RunFingerprinter for system reconnaissance, client.ClientSetup for HTTP client initialization, and client.RequestCommand for the C2 polling loop. The latter constructs and dispatches HTTP requests via net/http.NewRequestWithContext, net/http.(*Client).Do, and client.Middleware.

However, go_goroutines revealed that these application-level functions were absent from the captured call stacks. While awaiting a C2 response, the goroutine is parked by the Go scheduler with a select state, and the underlying network file descriptor concurrently enters an IO wait state until data becomes available, unwinding application frames and leaving only blocked standard library frames, such as net/http.(*persistConn).roundTrip. Despite this, go_goroutines recovered critical runtime artifacts by inspecting http.persistConn structures referenced from blocked goroutine stack arguments. It identified 31 goroutines (23 valid), of which 13 were actively involved in HTTP/TLS communication with the C2 server. Table 5

```

0x6e4561: lea    rax, [rip + 0x9d83d]          ; "/etc/sysconfig/vmp"
0x6e4568: mov    qword ptr [rsp], rax
0x6e456c: mov    qword ptr [rsp + 8], 0x12      ; = 18
0x6e4575: call   0x4d1700                      ; os.ReadFile
[Snip]
0x6e45ae: lea    rax, [rip + 0xa4c2e]          ; "/usr/java/jre-vmware/bin/upgrademgr"
0x6e45b5: mov    qword ptr [rsp], rax
0x6e45b9: mov    qword ptr [rsp + 8], 0x23      ; = 35
0x6e45c2: call   0x4d25c0                      ; os.Remove
[Snip]
0x6e45c8: lea    rax, [rip + 0xa4c14]          ; "/usr/java/jre-vmware/bin/upgrademgr"
0x6e45cf: mov    qword ptr [rsp], rax
0x6e45d3: mov    qword ptr [rsp + 8], 0x23      ; = 35
[Snip]
0x6e45fa: mov    dword ptr [rsp + 0x28], 0x1ed  ; = 493
0x6e4602: call   0x4d1aa0                      ; os.WriteFile
[Snip]

```

Figure 5: ABI-Aware Backward Analysis of `main.copyFile`

Table 3

BRICKSTORM main functions with recovered arguments. Highlighted cells indicate novel artifacts discovered by `go_functions`

Depth	Function	Recovered Arguments	Forensic Significance
main.main (Entry Point) [0x6e4da0]			
1	main.startNew	–	Initialization and persistence
	→ os.Getenv	"PATH", "TERM", "USER", "KENSO"	Environment reconnaissance / kill switch
	→ main.copyFile	–	Payload installation
2	→ os.ReadFile	"/etc/sysconfig/vmp"	Embedded payload retrieval
	→ os.Remove	"/usr/java/jre-vmware/bin/upgrademgr"	Pre-installation binary removal
	→ os.WriteFile	"/usr/java/jre-vmware/bin/upgrademgr", 0755	Trusted-path binary replacement
1	→ os.Setenv	"PATH", "/usr/java/jre-vmware/bin/"	PATH hijacking
	→ os/exec.Command	"upgrademgr"	Payload execution
	→ os.Exit	0	process termination
main.selfWatcher (Process Watchdog) [0x6e39a0]			
1	os.Getenv	"ENVLOG"	Operator-controlled runtime mode
	wssoft/libs/utls.HasExistProc	"upgrademgr"	Process existence verification
	os.ReadFile	"/etc/sysconfig/vmp"	Payload retrieval for self-reinstallation
	os.WriteFile	"/usr/java/jre-vmware/bin/upgrademgr", 0755	self-reinstallation
	os.Setenv	"PATH", "/usr/java/jre-vmware/bin/"	Execution path restoration
	os/exec.Command	"upgrademgr"	Watchdog respawn
	time.NewTimer	0x2260ff9290000 (≈ 7 days)	Long-delay scheduling
	math/rand.Int63n	600 (0–10min), 7200 (0–2hr)	Randomized sleep and jitter
	runtime.selectgo	3 cases, block=true	Scheduler-mediated multiplexing
	os.(*Process).signal	–	Inter-process signaling
main.main (continued) — C2 Task Loop			
1	main.main.func1–func6	XOR key pairs (Table 4)	String deobfuscation
	wssoft/core/task.DoTask	0x798af8 (task config)	C2 command execution
	strings.Index	"exit"	C2 termination keyword
	time.Sleep	calculated from rand	Evasion delay
	os.Exit	200	Distinctive termination exit code

summarizes the recovered artifacts, including the C2 address (192.168.20.123:1337), API endpoints used for system fingerprinting (`/sysinfo`), command output exfiltration

(`/cmdoutput`), and command polling (`/getcmd`), a runtime-generated authentication token (5112caedfb3a), server responses, negotiated TLS 1.3 parameters, and X.509 certificate fields extracted from TLS buffers in Goroutine 32.

Table 4

Complete XOR Key Pairs Recovered from *BRICKSTORM* Memory

Function	Len	Key A (hex, little-endian qwords)	Key B (hex, little-endian qwords)	Decrypted String
func1	25	d88eeb0f9d5fc3a, c3cb8be38823922c, b1fd2c591f81753c, 30	f7a1d1a389a18852, ecf3a5dba61bbc14, c398592832f21b58, 49	https://8.8.8.8/dns-query
func2	25	1b67d2765502f10c, 54cfcf26fdae3805, 9ac28998a6fea591, 56	3448e80525768564, 7bfbe112d396163d, e8a7fce98b8dcbf5, 2f	https://8.8.4.4/dns-query
func3	25	74c4b1463d036b04, 26816391cf54809c, 2273df9d12618a88, a7	5beb8b354d771f6c, 09b84da8e16daa5, 5016aaec3f12e4ec, de	https://9.9.9.9/dns-query
func4	26	da62e026514ae0cb, 6f7aeb38cfed01f, 74af8230987fe0c5, 139f	f54dda55213e94a3, 5e4bc501e1d49e26, 11daf31deb1184ea, 6aed	https://9.9.9.11/dns-query
func5	25	c209a43124860499, 461eb55f0c04f616, b95f447c0bef12fe, 15	ed269e4254f270f1, 692f9b6e2235d827, cb3a310d269c7c9a, 6ac	https://1.1.1.1/dns-query
func6	25	8d93c87a64ed5031, 072864390872e841, eff656a7257d0c4e, ea	a2bcf20914992459, 28194a092642c670, 9d9323d6080e622a, 93	https://1.0.0.1/dns-query

Table 5

Runtime forensic artifacts recovered from Pantegana HTTP/TLS goroutines using go_goroutines

Goroutine ID	Wait Reason	Function (Frame)	Field	Recovered Value
C2 Server Configuration				
25, 29, 31, 33, 39, 57	select	net/http.(*persistConn).writeLoop	cacheKey.{addr; scheme}	192.168.20.123:1337; https
HTTP Request Buffers (Runtime-Constructed)				
39	select	net/http.(*persistConn).writeLoop	bw.buf	POST /sysinfo HTTP/1.1\r\nHost: 192.168.20.123:1337
25, 29, 31, 57	select	net/http.(*persistConn).writeLoop	bw.buf	POST /cmdoutput HTTP/1.1\r\nHost: 192.168.20.123:1337
33	select	net/http.(*persistConn).writeLoop	bw.buf	GET /getcmd HTTP/1.1\r\nToken: 5112caedfb3a
HTTP Response Buffers (Network-Received)				
24, 28, 30, 38, 56	select	net/http.(*persistConn).readLoop	br.buf	HTTP/1.1 200 OK\r\nDate: Sat, 27 Dec 2025 23:49
TLS Session State (Negotiated at Handshake)				
25, 29, 31, 33, 39, 57	select	net/http.(*persistConn).writeLoop	tlsState.Version, tlsState.CipherSuite, tlsState.HandshakeComplete	772 (TLS 1.3) 4865 (TLS_AES_128_GCM_SHA256) True
C2 Server Certificate (Network-Received)				
32	IO wait	internal/poll.(*pollDesc).waitRead	[]uint8 (DER)	Subject: C=US, ST=Hawaii
Connection Metadata (Kernel State)				
32	IO wait	net.(*netFD).Read	net; family; isConnected; Sysfd	tcp; AF_INET; True; fd=10
Main Client State				
1	select	net/http.(*persistConn).roundTrip	-	Main HTTP client blocked awaiting C2 response

```

Caller pc: 0x6e56c0, Caller Name: main.main.func1 [depth=1]
0x6e56c0: mov     rcx, qword ptr fs:[0xfffffffffffffff8]
0x6e56c9: cmp     rsp, qword ptr [rcx + 0x10]
0x6e56cd: jbe     0x6e57d8
0x6e56d3: sub     rsp, 0x68
0x6e56d7: mov     qword ptr [rsp + 0x60], rbp
0x6e56dc: lea     rbp, [rsp + 0x60] ; &stack[0x60]
0x6e56e1: xorps   xmm0, xmm0
0x6e56e4: movups  xmmword ptr [rsp + 0x47], xmm0
0x6e56e9: movups  xmmword ptr [rsp + 0x50], xmm0
0x6e56ee: movabs  rax, 0xd88eebd0f9d5fc3a
0x6e56f8: mov     qword ptr [rsp + 0x47], rax
0x6e56fd: movabs  rax, 0xc3cb8be38823922c
0x6e5707: mov     qword ptr [rsp + 0x4f], rax
0x6e570c: movabs  rax, 0xb1fd2c591f81753c
0x6e5716: mov     qword ptr [rsp + 0x57], rax
0x6e571b: mov     byte ptr [rsp + 0x5f], 0x30 ; = 48
0x6e5720: movups  xmmword ptr [rsp + 0x2e], xmm0
0x6e5725: movups  xmmword ptr [rsp + 0x37], xmm0
0x6e572a: movabs  rax, 0xf7a1d1a389a18852
0x6e5734: mov     qword ptr [rsp + 0x2e], rax
0x6e5739: movabs  rax, 0xecf3a5dba61bbc14
0x6e5743: mov     qword ptr [rsp + 0x36], rax
0x6e5748: movabs  rax, 0xc398592832f21b58
0x6e5752: mov     qword ptr [rsp + 0x3e], rax
0x6e5757: mov     byte ptr [rsp + 0x46], 0x49 ; = 73

```

Figure 6: ABI-Aware Backward Analysis of main.main.func1

These artifacts are constructed dynamically at runtime and are therefore inaccessible to static analysis.

As shown in Figure 7, go_strings recovered further heap-resident artifacts, including the C2 IP address, API endpoints used for system fingerprinting (/sysinfo), all of our reconnaissance commands (whoami, id, who, cat /etc/shadow), and their complete output. In total, go_strings recovered all the dynamic aspects of the malware, including C2 configuration, attacker-issued commands, exfiltrated outputs, and HTTP requests and responses.

5. Limitations and Future Work

Our framework currently targets x86-64 architecture, as it covers the majority of environments where Go malware is observed. Supporting ARM64 would require adapting the

ABI-aware backward analysis to different calling conventions and register sets. To this end, large language models present a promising direction for generalizing across architectures. Moreover, the current analysis focuses on argument recovery at call sites and within goroutine frames. Thus, extending dataflow tracking to local variables and return values would enable richer semantic analysis, including taint propagation and more complete execution reconstruction.

6. Conclusion

This paper presented our efforts in analyzing Go binaries in memory. Our proposed framework parses Go's embedded structures to recover function metadata, type descriptors, and interface tables, considering stripped and obfuscated binaries. Leveraging this metadata, it identifies heap objects, extracts dynamically allocated and static strings, and classifies functions by origin. Through ABI-aware backward analysis, it further reconstructs execution paths and argument values from call sites. Goroutine analysis extends these capabilities by capturing active functions and their runtime argument values. We implemented these capabilities as Volatility 3 plugins and evaluated them against real-world malware, such as *BRICKSTORM*, *Obscura*, and *Pantegana*. The results demonstrated recovery of critical forensic artifacts, such as C2 configurations, cryptographic keys, persistence mechanisms, and threat actor communication channels, including indicators and behaviours not reported in published threat intelligence.

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```
user1@ubuntu:~/volatility3$ python3 vol.py -f /mnt/hgfs/pantegana/Snapshot.vmem linux.go_strings.Go_Strings --pid 2795
```

Struct Addr	Data Addr	Length	Value	Struct Location	Data Location
0xc000200180	0xc00023a068	19	"192.168.20.123:1337"	heap	heap
0xc000182880	0xc0000141e0	16	"5112caedfb3a4a17"	heap	heap
0xc0000b6158	0xc0000f804b	7	"/getcmd"	heap	heap
0xc0001a0c98	0xc0001b637b	10	"/cmdoutput"	heap	heap
0xc00021e1e8	0xc00023a07b	8	"/sysinfo"	heap	heap
0xc0001804b0	0xc000194590	6	"whoami"	heap	heap
0xc0001806b0	0xc00019463c	2	"id"	heap	heap
0xc000180840	0xc000194740	3	"who"	heap	heap
0xc000192870	0xc0001a5200	15	"cat /etc/shadow"	heap	heap
0xc00018d6e0	0xc0000d9400	39	"uid=0(root) gid=0(root) groups=0(root)"	heap	heap
0xc00007d9e0	0xc0000d8000	5	"root\n"	heap	heap
0xc00018dad0	0xc000229400	298	"x pts/1 2025-12-27 17:49 (192.168.20.42)..."	heap	heap
0xc00018dec0	0xc000220800	748	"root:\$y\$j9T\$FLXbuv9M83ZY/ROMEAL21\$AdX.RJtCqn52jn..."	heap	heap
[Snip]					
0xc0001876e0	0xc000298000	4096	"HTTP/1.1 200 OK ... Successfully got system information"	heap	heap
0xc000272660	0xc000278000	4096	"HTTP/1.1 200 OK ... Successfully posted output"	heap	heap
0xc000198080	0xc0001c8000	164	"{"os":"linux","arch":"amd64","name":"rkclient",...}"	heap	heap

Figure 7: Runtime forensic artifacts recovered from Pantegana memory using go_strings

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