MRSH-MEM: Approximate Matching on Raw Memory Dumps

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IMF 2018 - Hamburg, 2018-05-08

Memory Analysis

Interpretation of Structures	Memory Carving
Framework interprets the complex system related structures, where Profiles interface images (Rekall/Volatility): ▸ formats of acquisition ▸ memory management ▸ underlying architecture ▸ OS meta structures ▸ different versions	Unstructured analysis extract content information out of memory dumps: ▸ string extraction ▸ file carver ▸ signature matching (YARA)

Memory Analysis

Interpretation of Structures	Memory Carving
+ detailed examination of manifold information	+ straight forward application
+ cross validation tasks	+ not reliant on OS related structures
- needs domain knowledge for application	- less insights and not so powerful
- needs maintance; understand and implement OS in framework	- carving approach for specific examination

Motivation of Memory Carving

1. Extend analysis by data-driven **cross validation**
   (e.g. avoid OS-structure based analysis)
2. Open new possibilities to counter **anti-forensics**
   (e.g. Williams and Torres [8]: irrelevant and non-existing meta structures)
3. Need **fast data reduction** methods similar to disk forensics
   (e.g. for whitelisting known or blacklisting malicious code)
4. Methods for **first or last resort of interpretation**
   (e.g. no adequate / matching profiles; missing patches)

Memory Carving - Code

- special focus on examination of code-related structures
  - Whitelisting of benign code
  - Blacklisting of malicious code
- **Loading executables could lead to major manipulations**: ELF/PE loader, offset patching, base relocations, page alignment, alternative instructions, ...

Memory Management

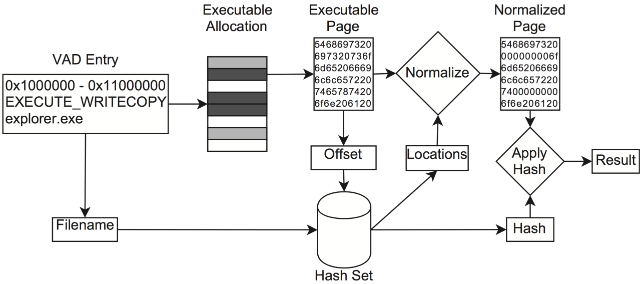
Beside the adaptations during loading, we should consider:

1. virtually contiguous $\neq$ **physically contiguous**
2. **page size** and **page alignment** could vary
3. **memory shared** between processes
4. not able to **resolve virtual address** without context
5. memory could be **swapped** to disk

Code integrity in memory - White et al. [7]

based on Walters et al. [6]

- Creates Hash-Templates of previously **normalized pages** (Hash-Templates are offsets + hash value)
- Imitates loading by a Virtual PE Loader
- Based on process identification (Filename)



Practical realization similar to White et al. [7]

inVteroJitHash

`https://github.com/K2/Scripting/blob/master/inVteroJitHash.py`

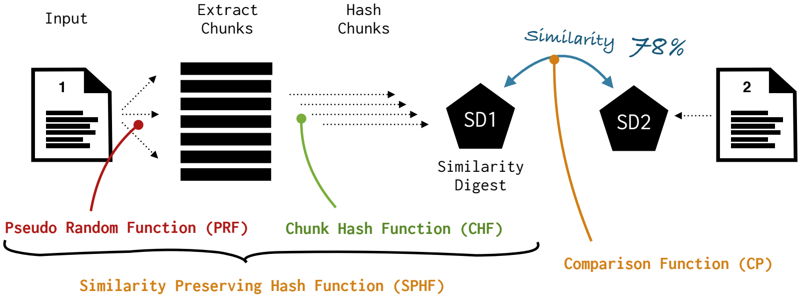
- Forensics, Memory integrity and assurance tool
- Server-based PE integrity hash database
- Send loading address and hash to server
- **Lifting** of the binaries and hashing on server side
- BlackHat USA '17

Summarized

- Most of the previous approaches rely on structural examinations and are process-context aware:
  → Process enumeration / reconstruction
  → Process identification
  → **Code normalization/lifting**
  → Integrity check (data reduction)

- We want to **carve code** in memory dumps **without recreating a process context**.
- *Could we utilize Approximate Matching for this task?*

MRSH Family [2, 3, 4]



- Sliding window rolls through byte sequence
- PRF defines chunk boundaries
- CHF compress the chunk
- MRSH-NET saves chunk in a single large Bloom filter (Hamming distance)

Memory forensics - impracticability

- **Bytewise** Approximate Matching respects every change in the underlying byte structure

  versus **mutability of code** in memory

↯ Influences **Chunk Extraction** (PRF)
↯ Influences **Chunk Hashing** (CHF)
→ Influences **Similarity Digest** itself

- We need an additional layer of **normalization** similar to Walters et al. [6] and White et al. [7]

Motivation

1. **Detect** sequences of code within raw bytes
2. **Normalize** detected code by disassembling

→ apply Approximate Matching on disassembled instructions

Definition: Approximate Disassembling should not provide a full decoding of the x86 complex instruction set. We decode for each instruction a representing mnemonic and length.

Raw bytes

```
41 55
48 89 f3
48 81 ec
```

→

Mnemonic + Length

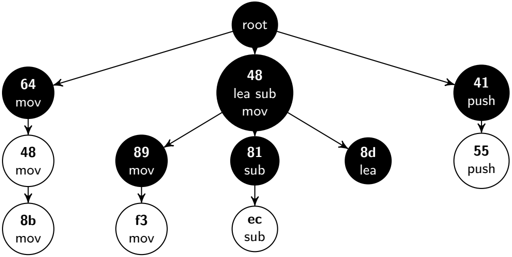
```
push 2
mov  3
sub  3
```

Classes of Disassemblers

- Disassembler for unknown x86/x64 instruction sequences
- Focuses on computational efficiency
- Discriminate code from data

Decoding	Length Disas.	Approximate Disas.	Linear Sweep	Recursive Traversal
Full	✗	✗	✓	✓
Mnemonic	✗	✓	✓	✓
Length	✓	✓	✓	✓
Linearity	✓	✓	✓	✗
Code Detection	-	✓	-	-
Interpretation	Bit	Byte	Bit	Bit

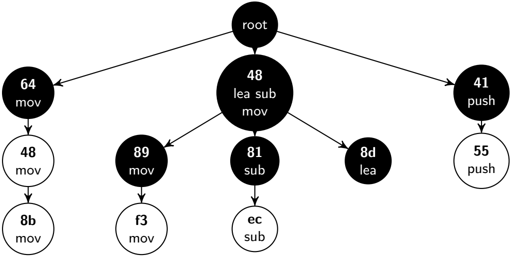
approxis [5] - Disassembling



Example: Simplified x64 instruction set!

- Build prefix-tree from a set of ground truth assemblies obtained by Andriesse et al. [1]
- Stay on a byte-level during disassembling; traverse tree

approxis [5] - Disassembling



Interpret the raw byte sequence with the generated prefix tree.

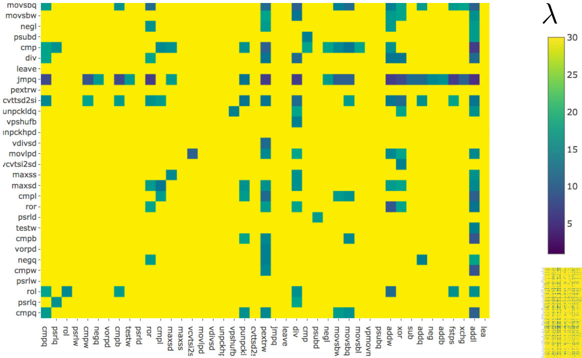
```
41 55 48 89 f3
48 81 ec 48 8d
64 48 8b
```

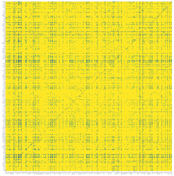
→

```
push  41 55
mov   48 89 f3
sub   48 81 ec
lea   48 8d
mov   64 48 8b
```

approxis [5] - Code Confidence

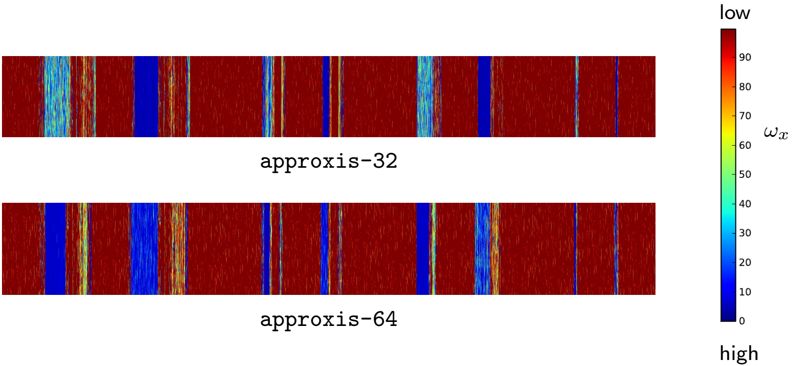
Mnemonic bigram frequencies as absolute logits: $\lambda = \left| \ln \frac{p}{1-p} \right|$





approxis [5] - Code Detection

- Interleaved 32 and 64 bit binaries into block of random data
- ω_x describes average confidence of current window at offset x



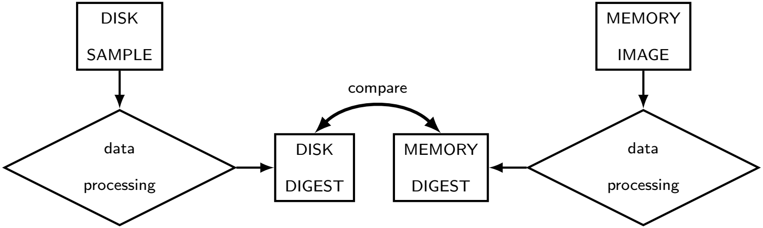
approxis [5] - Computational Performance

- Created three images with a size of 2 GiB
- Reduced diStorm: no output, large buffer, full decoding

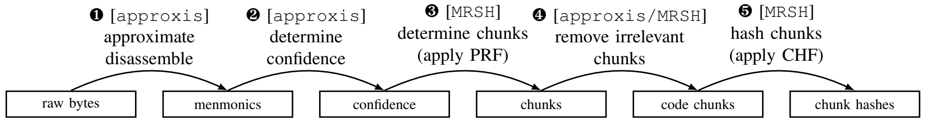
Execution time				Description
approxis		diStorm		disassembler
32	64	32	64	mode
29.084s	21.936s	1m20.770s	1m7.772s	64bit binaries from /usr/bin
27.859s	31.918s	1m43.999s	1m43.046s	Raw memory dump (LiME)
1m15.521s	1m44.990s	1m58.278s	1m56.192s	Random sequences (/dev/urandom)

Concept

- MRSH-MEM: integration of approxis into MRSH-NET
- Focus on computational efficiency
- From **Bytewise** to **Mnemonic-wise** Approximate Matching



MRSH-MEM - Processing Pipeline



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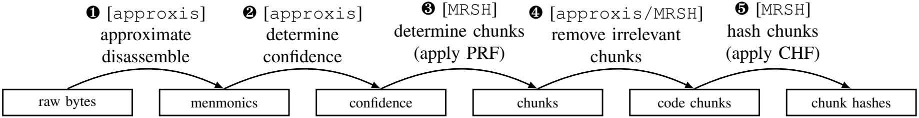


raw bytes	menmonics	confidence	chunks	code chunks	chunk hashes
Byte	MNE : Byte	MNE : λ	MNE : Chunk	MNE : Chunk [CF]	Chunk : Hash
00 00 00	000 : 00	000 : 64	000 : C_1	000 : C_1	092 : C_2
31 ed 49	000 : 00	000 : 64	000 : C_1	000 : C_1	095 : C_2
89 d1 5e	000 : 00	000 : 63	000 : C_1	000 : C_1 [0]	105 : C_2
48 89 e2	092 : 31 ed	092 : 12	092 : C_2	092 : C_2	095 : C_2 [5AC]
48 83 e4	095 : 49 89 d1	095 : 09	095 : C_2	095 : C_2	
f0 00 00	105 : 5e	105 : 11	105 : C_2	105 : C_2	
00 00 00	095 : 48 89 e2	095 : 10	095 : C_2	095 : C_2 [1]	
	090 : 48 83 e4 f0	090 : 10	090 : C_3	090 : C_3	
	000 : 00	000 : 64	000 : C_3	000 : C_3	
	000 : 00	000 : 64	000 : C_3	000 : C_3	
	000 : 00	000 : 64	000 : C_3	000 : C_3 [0]	

MRSH-MEM - Technical Details

- Detailed example in the paper
- Strongly interleaved implementation
- Usage of **multiple buffers**, e.g.:
  1. Raw byte buffer
  2. Integerized mnemonic buffer
  3. Relative offset buffer

  ...
- Usage of **multiple parameters**, e.g.:
  1. Block size
  2. Code confidence threshold
  3. Code coverage per block

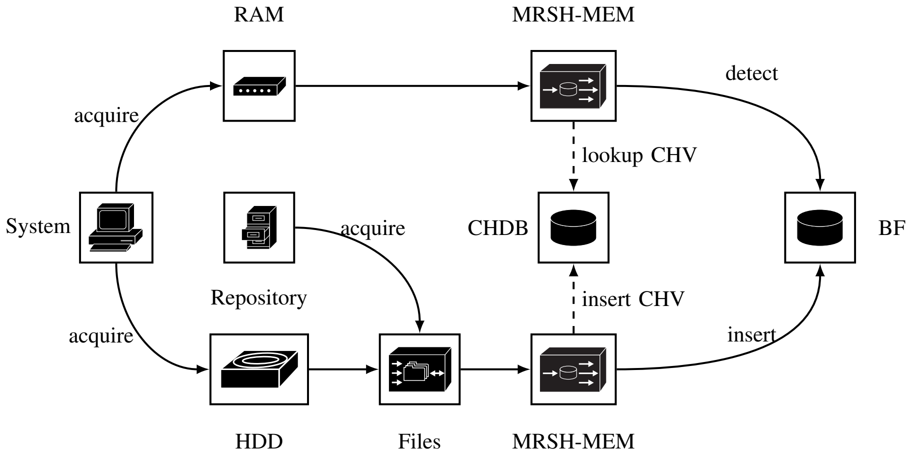
  ...

Concept

- MRSH-MEM uses a single, large Bloom filter → disadvantage: **Lack of file identification**: the approach can only answer the question if a file is contained in a given Bloom filter, but we cannot say to which file a similarity exists.

  temporal solution CHDB:
  - database of extracted chunk hash values (CHV)
  - chunk hash database (CHDB) consists of single lookup tree
  - each leaf node with corresponding file name(s)

Concept Overview



Target System

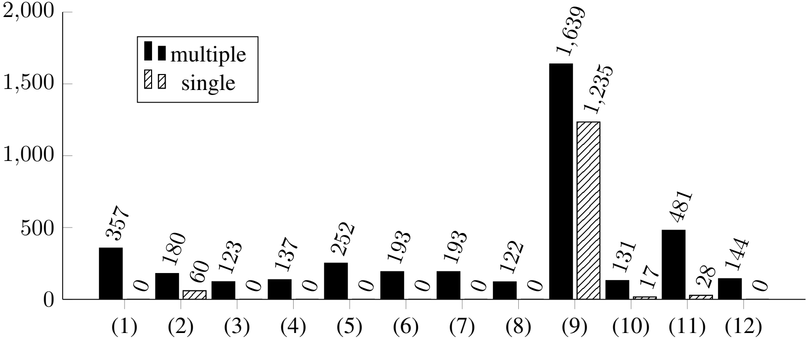
- Debian 8 installation (Debian 3.16.7 x86 64 GNU/Linux)
- Virtual Box (Version 5.2.6 r120293)
- Network analysis tasks
- Acquire dump with LiME 7 (Linux Memory Extractor)

Examination 1) Kernel Version

- Determine the running kernel version of an acquired dump
- Extracted 12 Linux Kernel images from the Debian repository
- Present Kernel: **3.16.0-4-amd64** (9)

ID	Kernel	ID	Kernel
(1)	3.2.0-4-amd64	(2)	4.13.0-0.bpo.1-amd64
(3)	4.14.0-0.bpo.2-rt-amd64	(4)	4.14.0-0.bpo.3-amd64
(5)	3.2.0-4-rt-amd64	(6)	4.14.0-3-amd64
(7)	4.15.0-rc8-amd64	(8)	4.14.0-0.bpo.2-amd64
(9)	**3.16.0-4-amd64**	(10)	4.14.0-3-rt-amd64
(11)	3.16.0-0.bpo.4-amd64	(12)	4.14.0-0.bpo.3-rt-amd64

Examination 1) Kernel Version

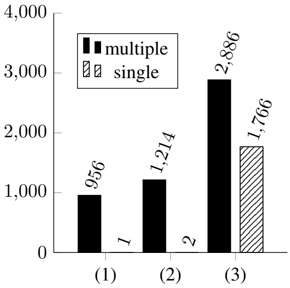


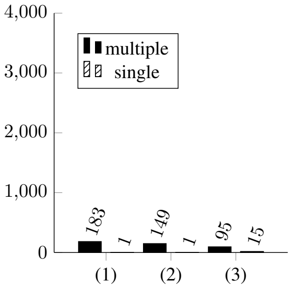
- single hits clearly identify correct running kernel version

Examination 2) Running Application

ID	Version	ID	Version	ID	Version
(1)	2.4.4-1_amd64	(2)	2.2.6*_amd64	(3)	**1.12.1*_amd64**

- Acquired two memory dumps of target system **with** running and **without** running Wireshark instance





Runtime Performance

Execution time insert	Execution time lookup	Chunks	Description
46.0s	48.0s	6,887,955	Concatenated set of 64bit binaries from `/usr/bin`
50.0s	50.0s	1,608,674	Raw memory dump acquired with `LiME`
197.0s	192.0s	10,537,710	Random sequences of bytes generated with `/dev/urandom`

- `Intel(R) Core(TM) i5-3570K CPU @ 3.40GHz`, `16 GiB DDR3 RAM (1333 MHz)` and `6 MiB L3` cache
- Prototype in `C` (`-O3`)
- Created three images with a size of `2 GiB`
- 64 bit case; Bloom filter only

Conclusion

- Discuss the considerations and limitations by applying Approximate Matching on code located in memory
- Introduced a new specimen of Approximate Matching: `MRSH-MEM`
- Demonstrated a first use case by comparing a memory dump with code fragments of different resources

- More details given in our paper
- Release prototype
  `https://github.com/dasec/approximate-memory`

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Future Wok

1. Database Lookup Problem (CHDB replacement)
2. Better verification (Synthetic Carving Images)
3. Extend by Windows-based analysis (in 2018)
4. Integration into framework-based analysis (e.g. as plugin for Volatitliy, Rekall)

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