Quantifying Paging on Recoverable Data from Windows User-Space Modules

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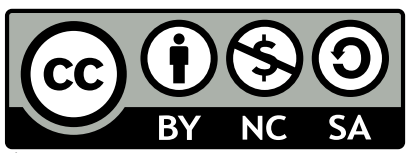

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Outline

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Introduction

Memory forensics

Memory dump

- **Full of data** to analyze
- **Each item that can be analyzed is called *memory* artifact**
  - Retrieved via appropriate internal structures of the OS or using a pattern-like search
- Snapshot of running processes, logged in users, open files, or open network connections – **everything that was running at the time of acquisition**
- May also contain **recently freed system resources**
  - Normally, memory is not zeroed when freed
- Volatility: **de facto standard** tool for analyzing memory dumps
  - Version 2 vs. version 3 ⇒ Python2 vs. Python3

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Introduction

A little more of recap...

Malicious software (malware) analysis

- Determine *what the heck* the malware does as harmful activities
- **Static analysis**: executable files are analyzed without being executed
- **Dynamic analysis**: executable files are analyzed when run

Malware in memory

- Unless memory hardware-protection mechanisms are in place, running malware will leave traces of its nefarious activity in memory
- More likely evidence of activity from sophisticated or fileless malware
- We focus on Windows, as it is still the most predominant target of attacks

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Introduction

The Windows memory subsystem

- **Maps a process virtual address space into physical memory**
- **Manages memory paging**: memory pages are...
  - Paged to disk when the demanding memory of running threads exceeds the available physical memory; and
  - Returned to physical memory when needed

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Memory page

- **Contiguous fixed-length block of virtual memory**
- Small (4 KiB) and large pages (2 MiB [x86 & x64] to 4 MiB [ARM])
- **Different states**: free, reserved, and committed

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Introduction

Terminology

- **Image**: executable, shared library, or driver file loaded as part of a process
- **Image file**: the corresponding (on-disk) file
- Processes and images are internally represented by a **module**

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Contribution

- Analysis of how paging issues affect the user-mode Windows modules
- Discussion on the issues to detect malware artifacts in memory forensics
- As a side product, `residentmem` Volatility plugin
  - Provides information on the amount of binary data that cannot be analyzed correctly

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Related work

- **Identify all user allocations and determine their purpose** using kernel & user-space metadata sources via Virtual Address Descriptors (VAD)
- **Parse of PTE in Linux via a kernel module** (`PageDumper`)
- **Malware detection in memory forensics**
  - VMI, YARA, machine learning approaches
  - Detection of hidden malware via PTE or GPU memory

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- **First study that quantifies the effect of paging in Windows user-space modules**
- Our work is **complementary to all those**

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Characterization of the Windows paging mechanism

- **Paging issues in user-space modules** on a Windows 10 64-bit system (build 19041) with 4GiB and 8GiB RAM memory
- **Different memory workloads**: 25%, 50%, 75%, 100%, 125%, and 150%
  - We developed a naif tool that allocates memory and writes a random byte every 4KiB

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- System memory acquired at various runtimes for each memory workload
  - *First observation moment*: every 15 seconds for the first minute, every minute for 4 more minutes, while allocating memory
  - *Second observation moment*: same pattern, after stopping the memory allocator tool

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- **Side product of our research**: `residentmem`
  - Volatility2 plugin, GNU/GPLv3. `https://github.com/reverseame/residentmem`
  - Extracts the number of resident pages (that is, in memory) of each image and each process within a memory dump
  - Provides forensic analysts with information on the amount of binary data that cannot be analyzed correctly

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Characterization of the Windows paging mechanism

Description of the plots

- **Distributions of two variables**
  - Size of a module file in log-base 10 (x-axis)
  - Percentage of resident pages (y-axis)
- Color intensity: **the darker the region, the more data is in that region**
- **Subplots reveal the distribution** of resident pages and module file sizes

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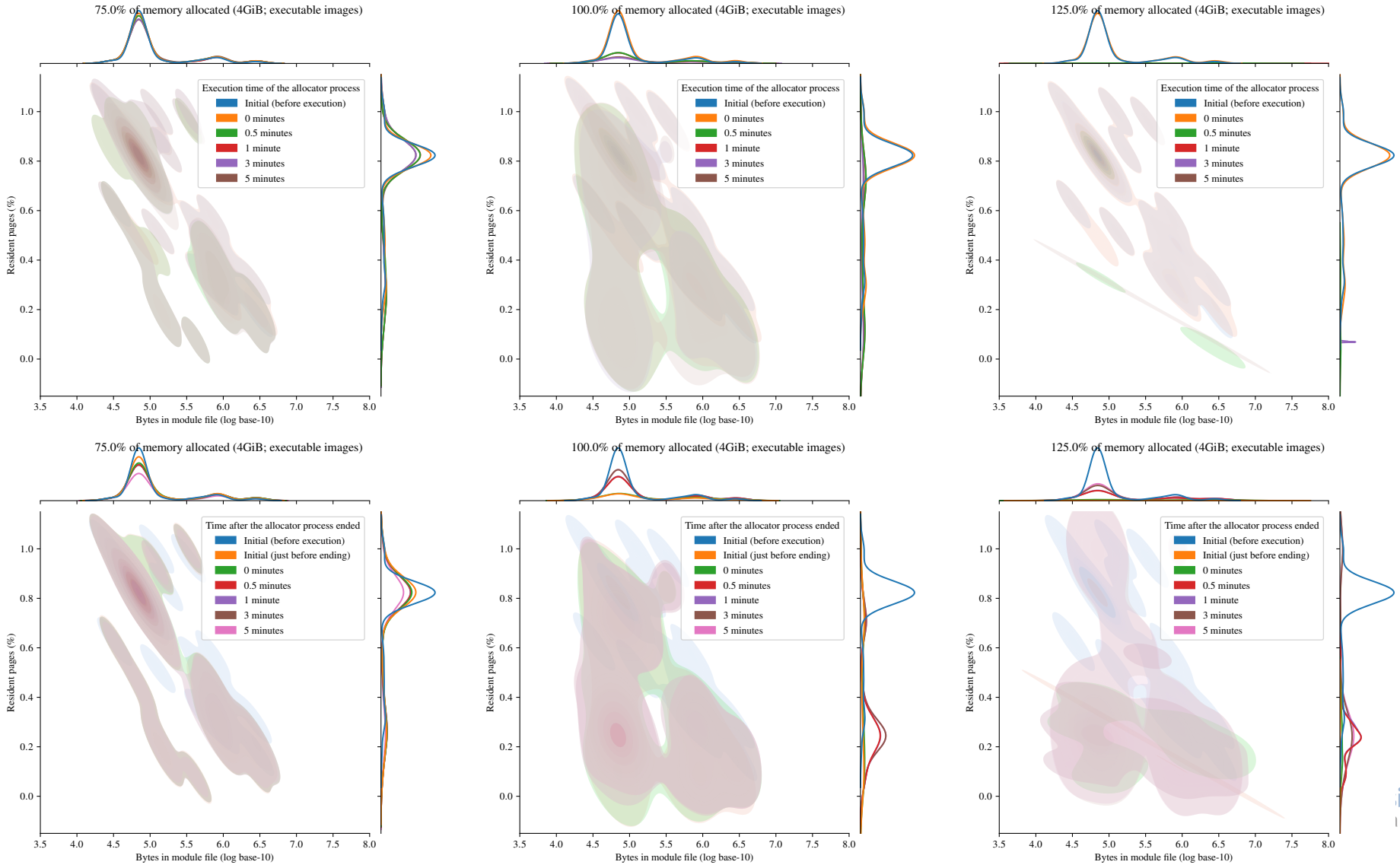
Characterization of the Windows paging mechanism

Results of quantification (4GiB; `exe`)



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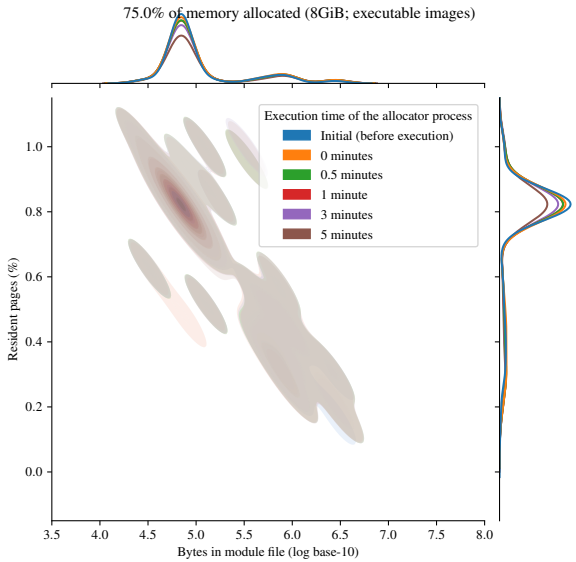

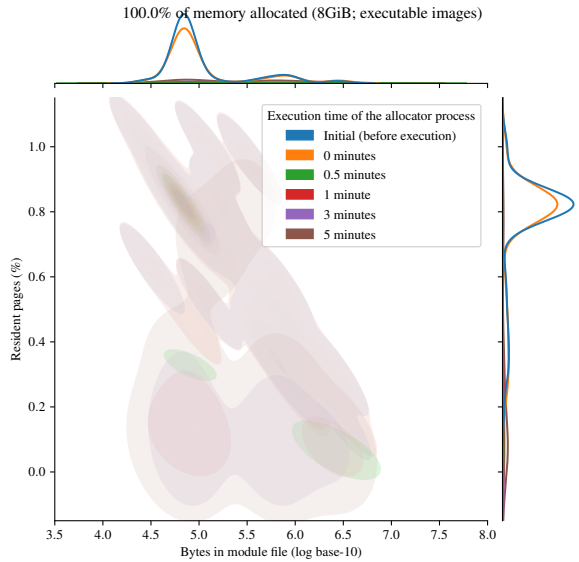

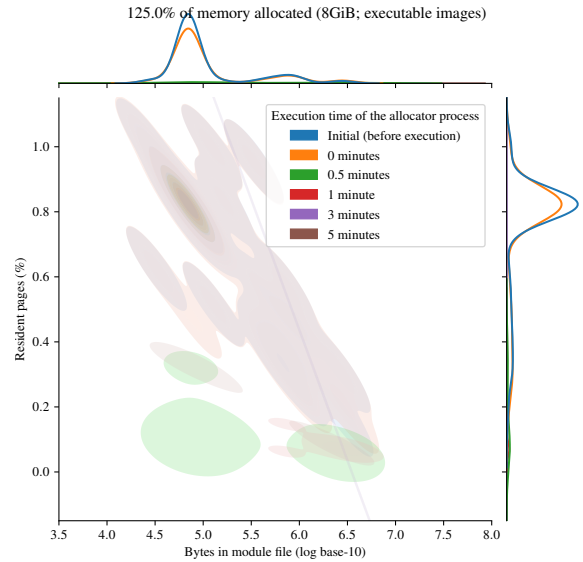

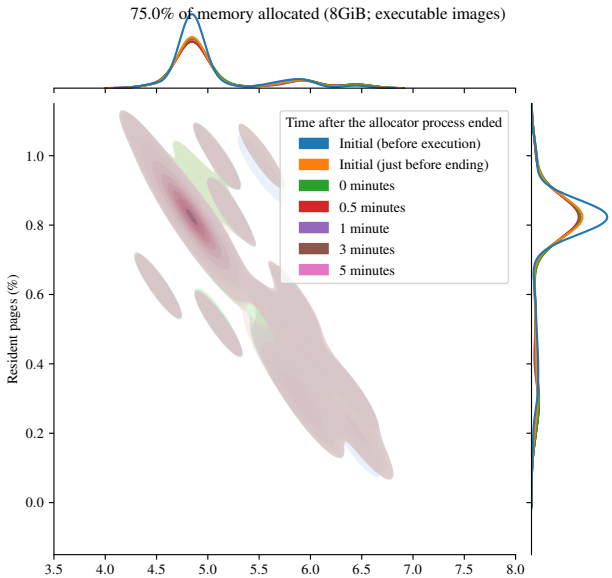

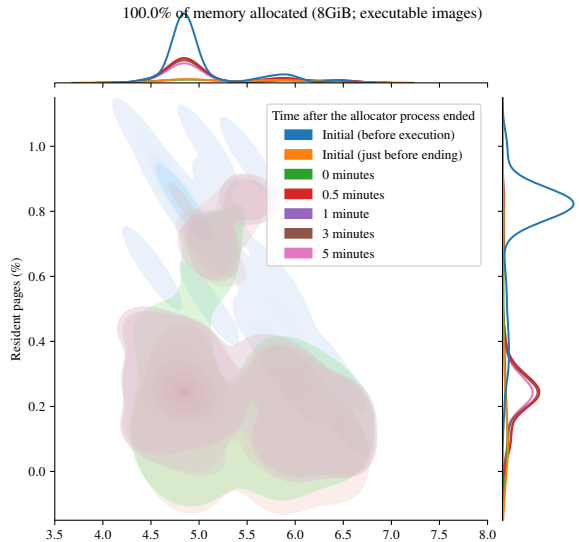

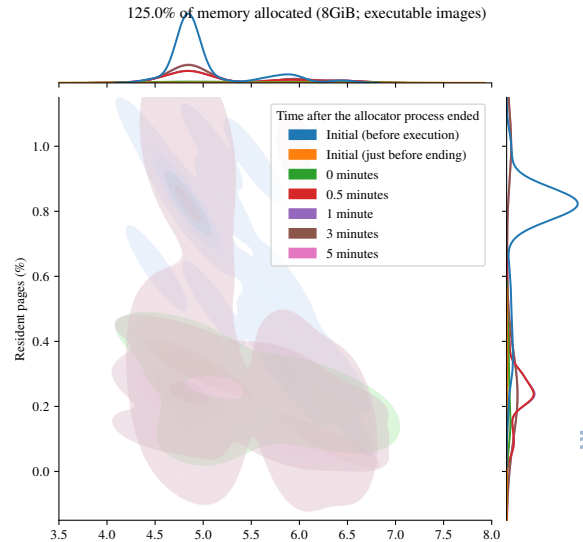

Characterization of the Windows paging mechanism

Discussion on executable modules

- **Almost 80% of the executable module pages are resident** in memory
- With 100% and 125%, in 0.5 minutes:
  - **Most modules are expelled**
  - The number of resident pages for retrievable modules is drastically reduced
- Modules progressively come back to memory, after memory exhaustion
  - **Ratio of resident pages for retrievable modules** $\leq 25\%$
  - Significant increases in 0.5 minutes and in 3 minutes are observed

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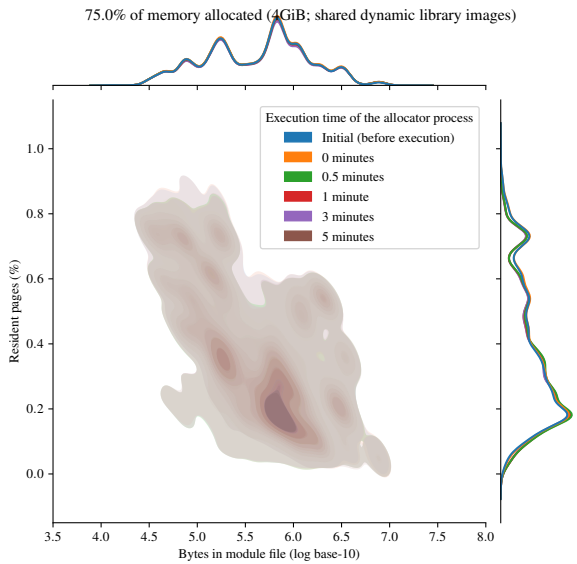
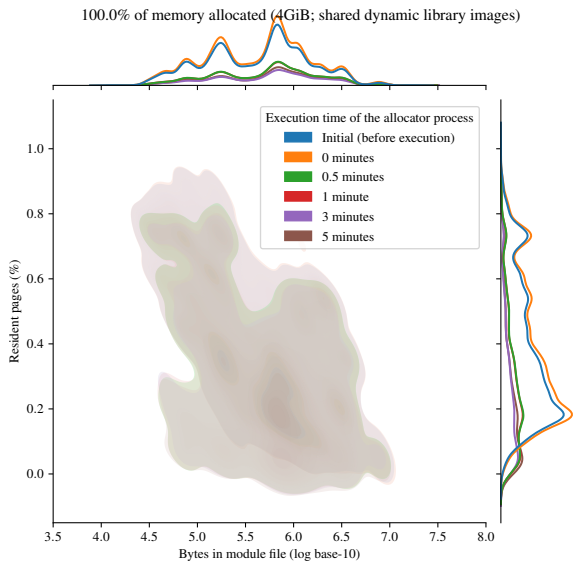
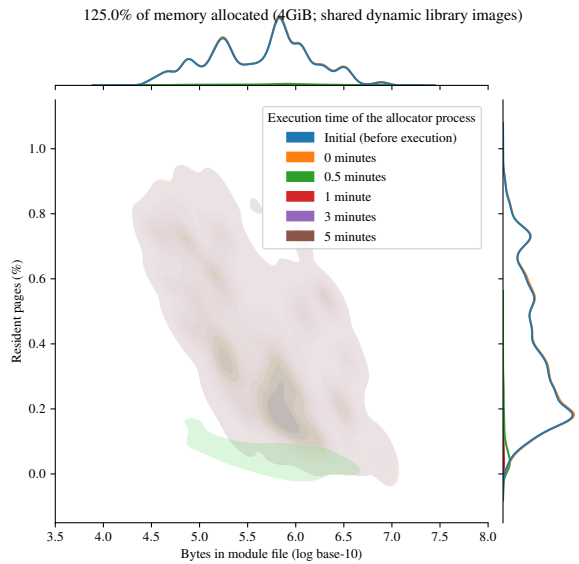
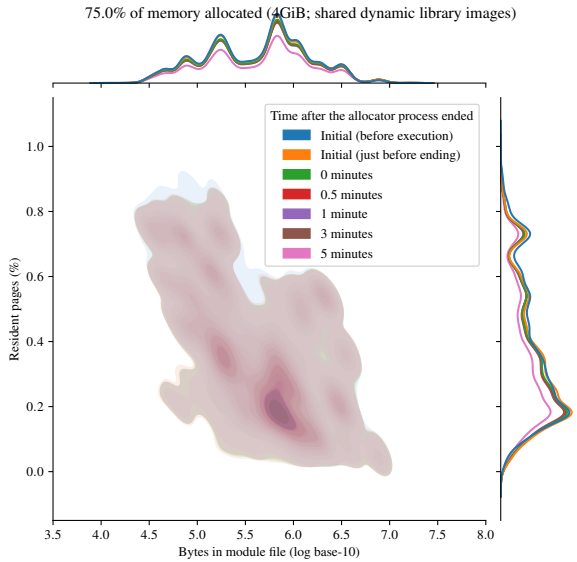
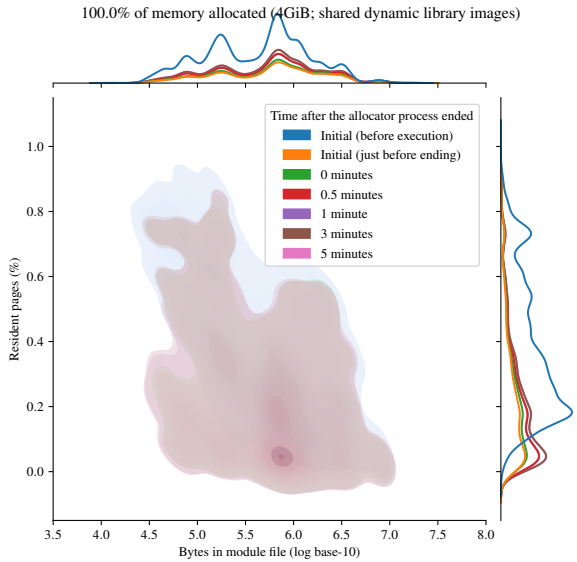
Results of quantification (4GiB; `dll`)

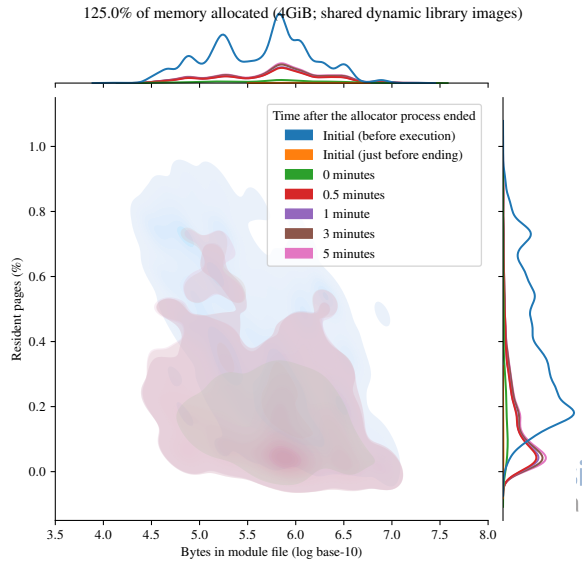






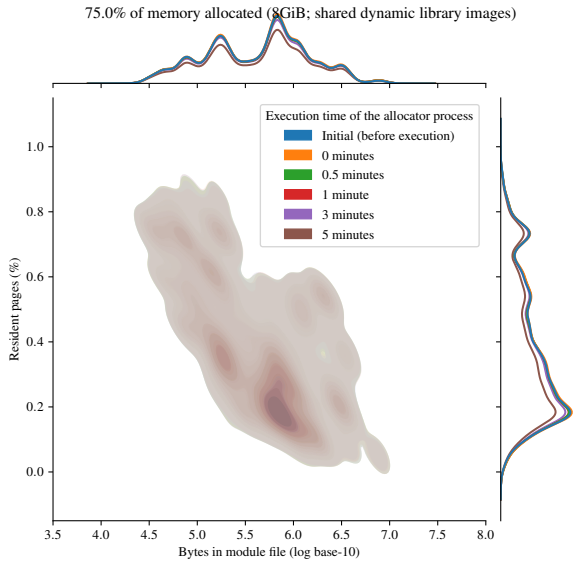


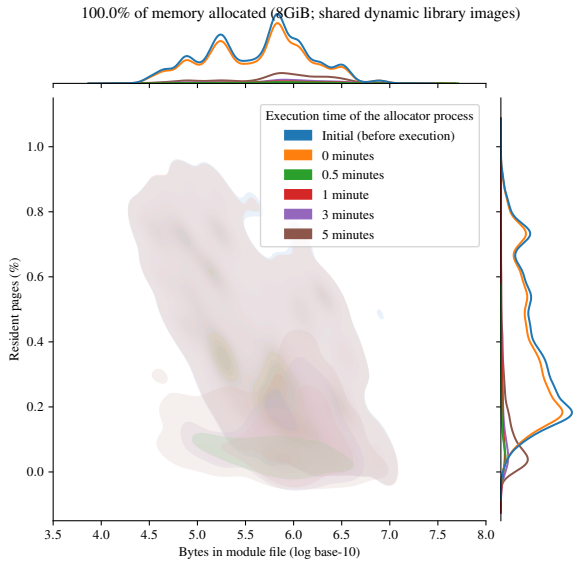


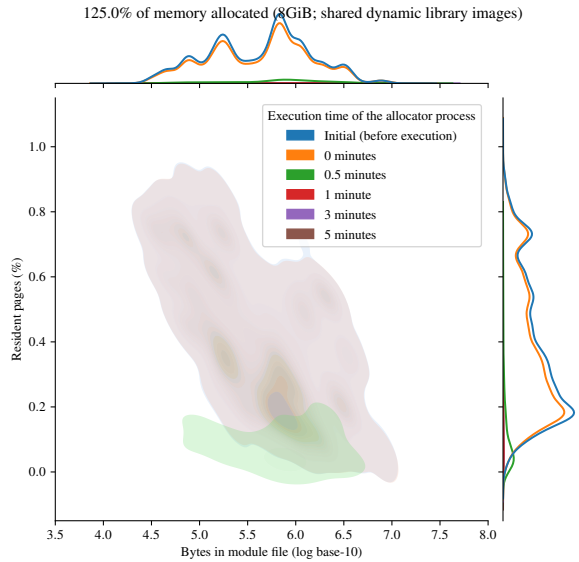


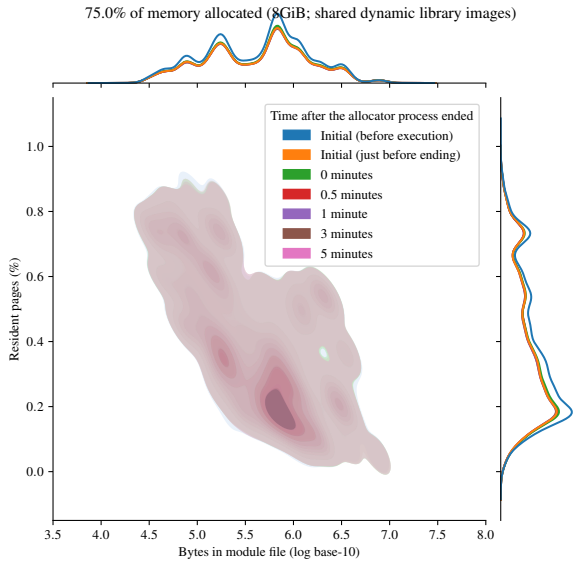
Characterization of the Windows paging mechanism

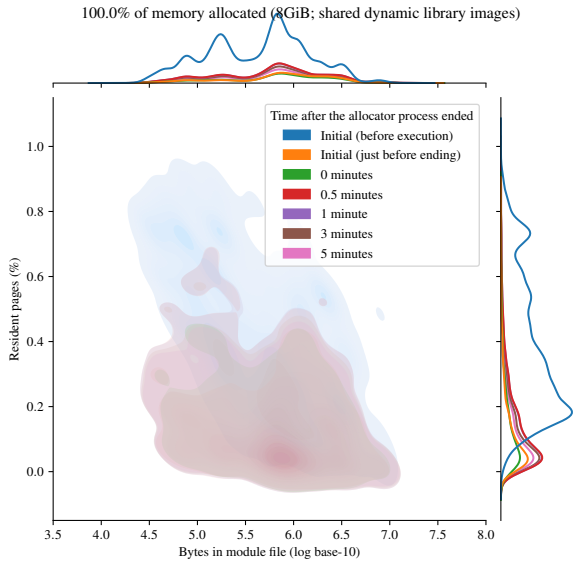
Results of quantification (8GiB; `dll`)

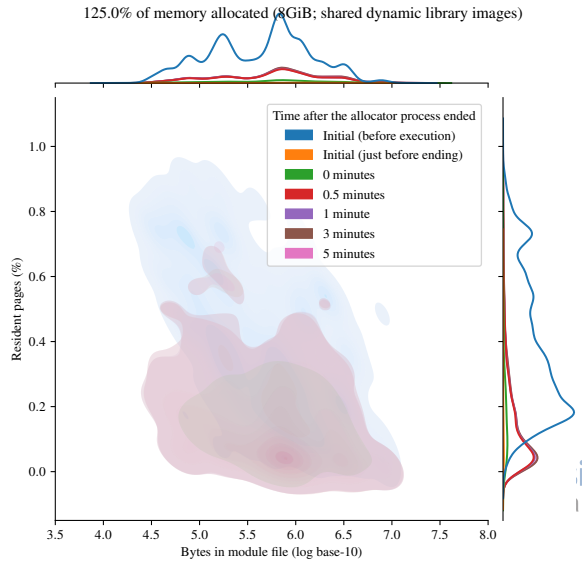












Characterization of the Windows paging mechanism

Discussion on shared library modules

- Modules only have **20% of their pages resident**, with a maximum percentage observed of 75%
- With 100% and 125%, **in 0.5 minutes the system starts expelling them**
  - Distribution shape is similar in both memory configurations
  - Aggressive expelling of modules is observed in 8GiB
- **Most modules have only less than 5% of their pages resident, after memory exhaustion**

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Detection of Malware in Memory Forensics

Inaccuracy of the content of memory artifacts

The content of an image is inaccurate
(relative to its image file)

Everything happens for a reason...

- **Paging effect**
  - Image file mapped into 4KiB aligned memory regions (assuming small pages)
  - As a consequence, a zero padding may appear
- **Relocation**
  - Addresses of external functions resolved (e.g., IAT functions)
  - PE sections removed (e.g., `.reloc` or Authenticode signatures)

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Feasible solutions

- Use approximate matching algorithms to calculate similarity
- Constructions of allow-list hash databases

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Detection of Malware in Memory Forensics

Incompleteness of images

The content of an image is incomplete

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Everything happens for a reason...

- **Page swapping**
  - The OS stores unused memory pages in a secondary source until those pages are needed again
  - Allows us to use more memory than is actually available in RAM
- **Demand paging** (or *lazy page loading*)
  - The OS does not bring data from files on disk to memory until it is absolutely necessary
  - Optimization issue

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Feasible solutions

- Use disk forensics to first recover the page files and then use them together with the memory dump
- Combine memory forensics with disk forensics

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Detection of Malware in Memory Forensics

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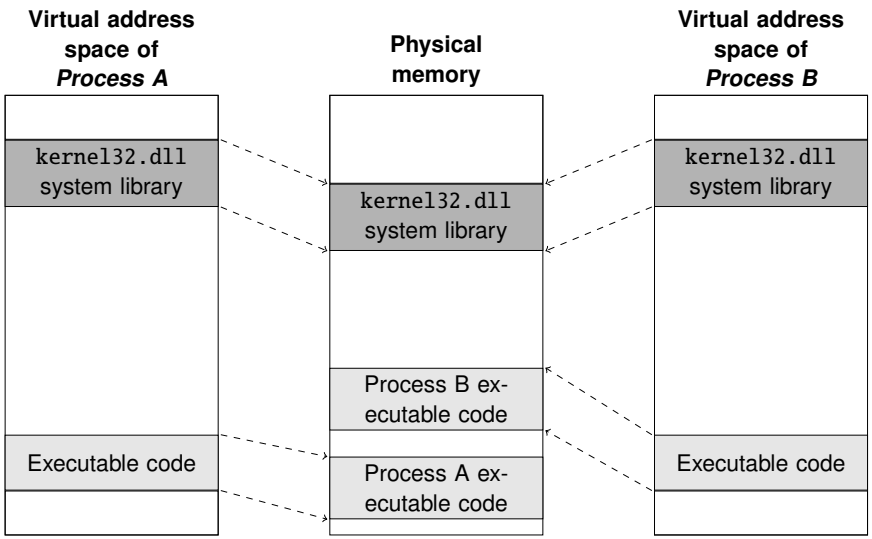

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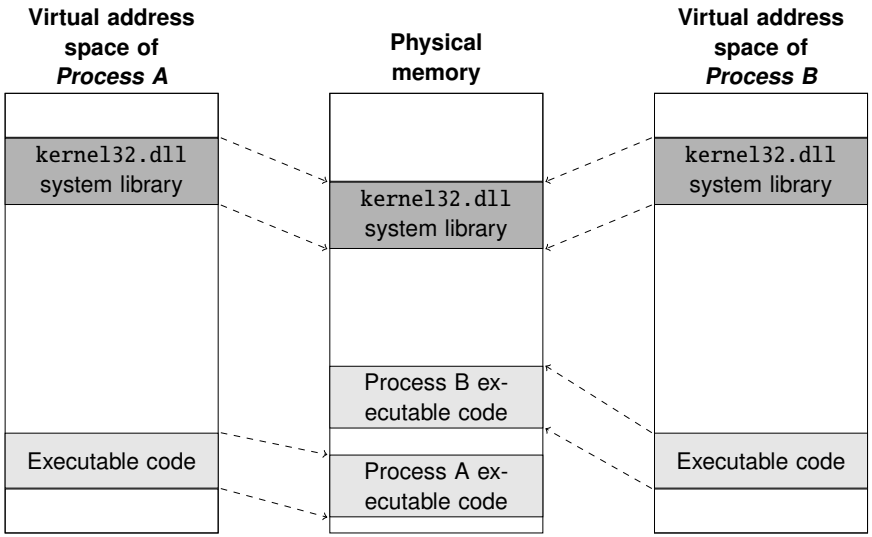

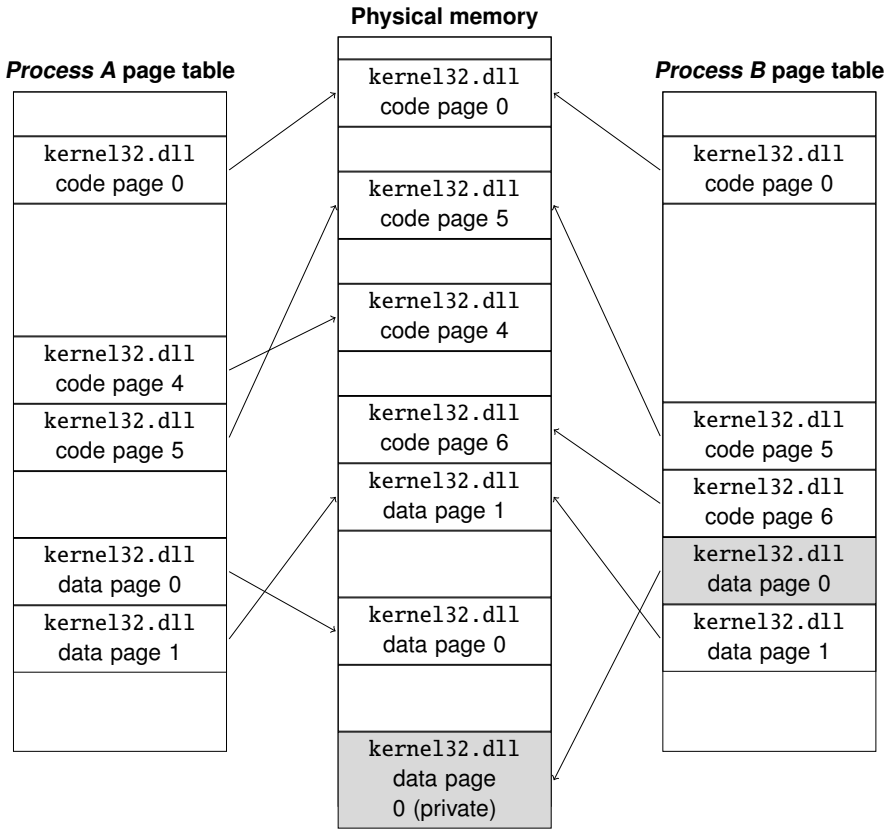

Detection of Malware in Memory Forensics

Inaccuracy of a memory dump

- Memory is **continually updated and acquired non-atomic**: *page smearing*
  - Particularly relevant when the memory is acquired in a live system
- Highly likely to occur:
  - **Pointer inconsistency**
  - **Fragment inconsistency**
- **Sophisticated malware can deliberately produce these inconsistencies** (DKOM attacks)

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Feasible solutions

- Use other acquisition techniques
- Check the temporal consistency of data in a memory dump: *temporal forensics*

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Detection of Malware in Memory Forensics

Stealthy malware

- VAD are **unreliable source of information**
  - Page permissions are not updated when changed after initial permissions
- **Deliberately triggering of the paging process** for as many pages as possible
- **Process hollowing**

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Detection of Malware in Memory Forensics

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Feasible solutions

- Malware signatures (but not with cryptohashes!)
- Robust kernel signatures
- Volatility plugins: `malfind`, `malscan`, `impfuzzy`

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Conclusions

- **Memory dumps are unreliable and partial sources of evidence**
- **Effect of paging in Windows modules of the user-space processes**
  - At first, almost 80% of the executable module pages and 20% of the shared dynamic library module pages are resident. Drastically reduced when the OS needs memory
  - Once the memory load is no longer high, the system recovers some of the paged modules but very slowly, never returning to the initial conditions (25% and 5% for executable and shared library image files, respectively)
- **Problems for malware detection in memory forensics**
  - Data in an image differs from its image file and is incomplete, inaccurate, and unreliable
  - Malware can incorporate features to remain stealthy and hidden from memory forensics

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Future work

- Study other versions of Windows, apart from Windows 10 (build 19041)
- Better characterize paging distributions under different system workloads
- Quantify the effects of paging on the kernel space
- Investigate new methods to detect stealthy malware in memory forensics

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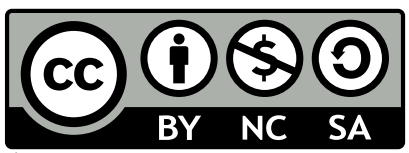

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