Memory Forensics

Andrea Oliveri
andrea.oliveri@eurecom.fr

speaker@localhost:~$ whoami

Andrea Oliveri (a.k.a. Iridium)

###

-> PhD student at Eurecom in S3 research group, under the supervision of Prof. Davide Balzarotti.

Research interests:

-> Zero-knowledge memory forensics

-> Reversing engineering

-> CPUs/machines architectures

-> Network security

###

EURECOM
Sophia Antipolis

- **International University** (*Grande École*) and **research center** in digital sciences in Sophia-Antipolis (**France**)
- **9 universities and 7 industry partners**
- **3 principal research themes:**
  - Telecommunication
  - Data science
  - **Cybersecurity**
- **4 ERC grants**

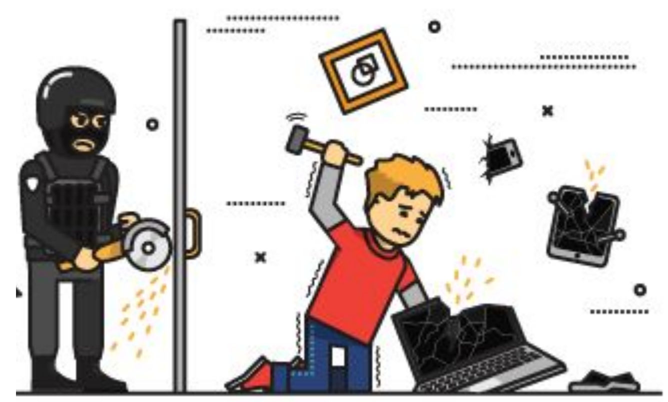
Software and system security group (S3)

- **3 faculty members:**
  - Prof. Davide Balzarotti
  - Prof. Aurelien Francillon
  - Prof. Daniele Antonioli
- **1 Post-Doc**
- **13 PhD students**

- **Research areas:**
  - **Android Security**
  - **Malware Collection, Detection and Analysis**
  - **Memory Forensics**
  - **Security in Embedded Systems**
  - **System Security**
  - **Web Security**

What is digital forensics?

Digital forensics is the **application of investigation and analysis techniques to gather and preserve evidence** from a particular computing device

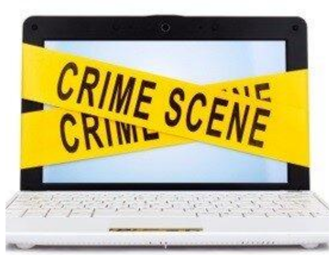


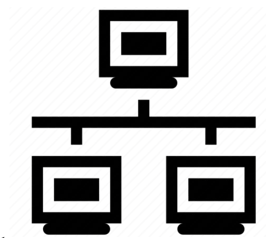
Why digital forensics?

- Police investigation

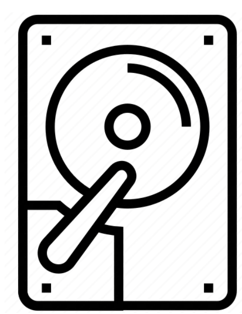
- **Incident response**
- **Malware analysis**

Where are the evidence?



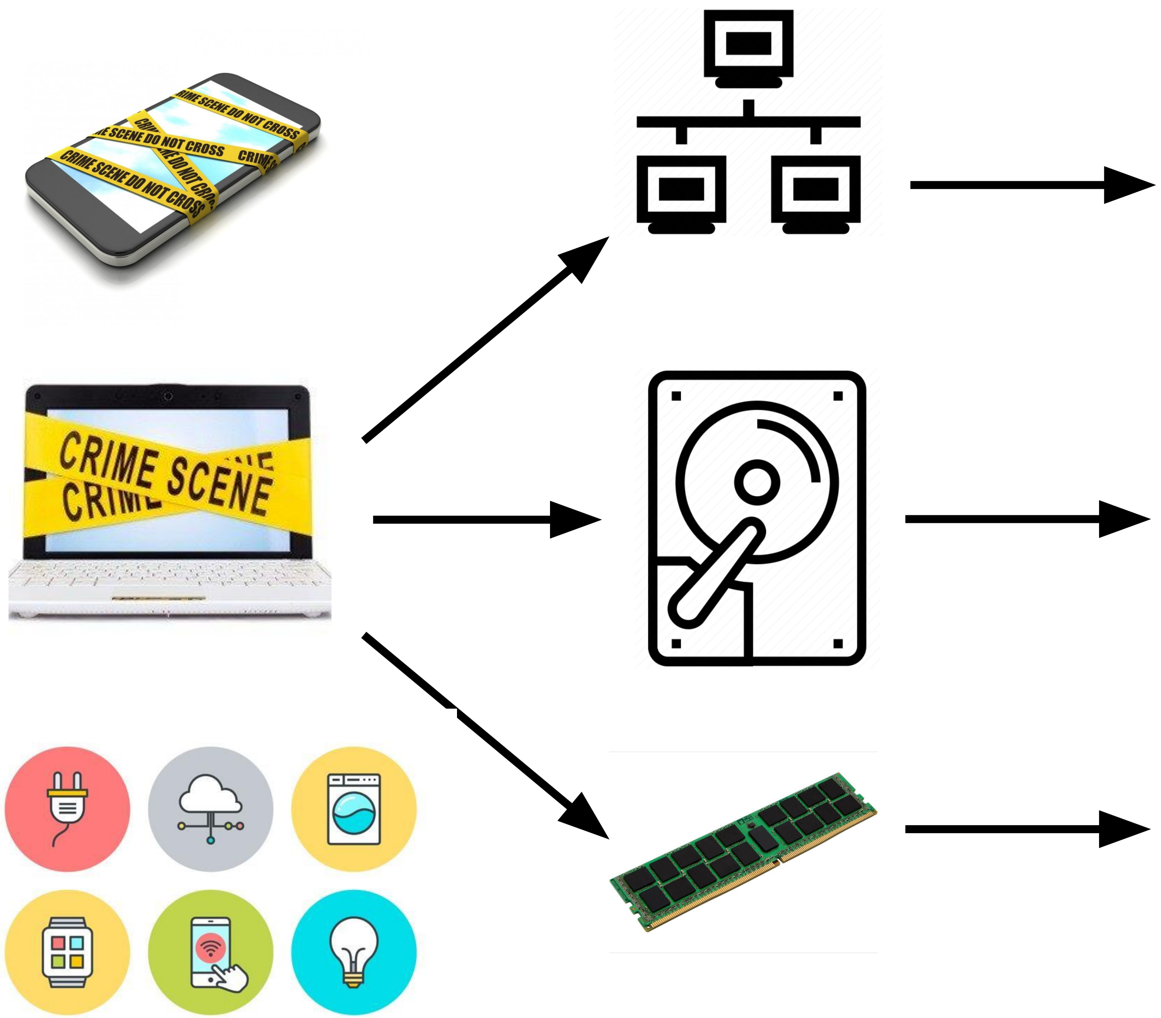


- Packets and connections
- Services
- Transferred data
- Firewall logs



- Volumes and partitions
- File systems
- Data in empty regions
- OS & apps artifacts

Where are the evidence?



- Packets and connections
- Services
- Transferred data
- Firewall logs

- Volumes and partitions
- File systems
- Data in empty regions
- OS & apps artifacts

- Volatile memory (RAM)

Memory Forensics

The process of capturing a copy of the system memory (RAM) and extracting a number of artifacts that are useful for an investigation

- Essentially, **it consists in:**
  - **Acquiring a snapshot** of the system memory
  - **Locating known data structures** in the raw image to extract OS and process information
  - **Carving** de-allocated data structures, strings, encryption keys, credit card numbers…

- Relatively new field (~2005), and still a very active research area

Available Information

- **Running, terminated, and hidden processes**
  - Code, data, open files, buffers, ...
- **Kernel modules**, drivers and privileged services
- **Hardware devices** connected at dump time
- Open **sockets** and active **connections**
- **Memory-mapped files**
  - Executables, shared libraries, ...
- **Clipboard's content**
- **Browsers data**
  - History, cached pages, passwords, ...
- **Cached data**
  - Open documents, emails and IM messages, ...

Memory Forensics - Pro

- **Memory is relatively small** compared to hard disks
- **Attackers often overlook their memory footprint**
- Many of the **kernel artifacts can be used for forensics**
- Even **rootkits** designed to hide data in a running system **need to be located somewhere in memory**
- **Certain information** (loaded kernel modules, open sockets, ...) may be **difficult to extract otherwise**
- Some **malware samples only reside in memory**

Memory Forensics - Cons

- On physical machines **the content of the memory keeps changing**
  - Data collection **requires an efficient approach with a small footprint**
  - Consecutive imaging acquisitions **give different results**
  - **Forget about comparing hashes**

  ⇒ **It is impossible to verify the authenticity of the acquired data**

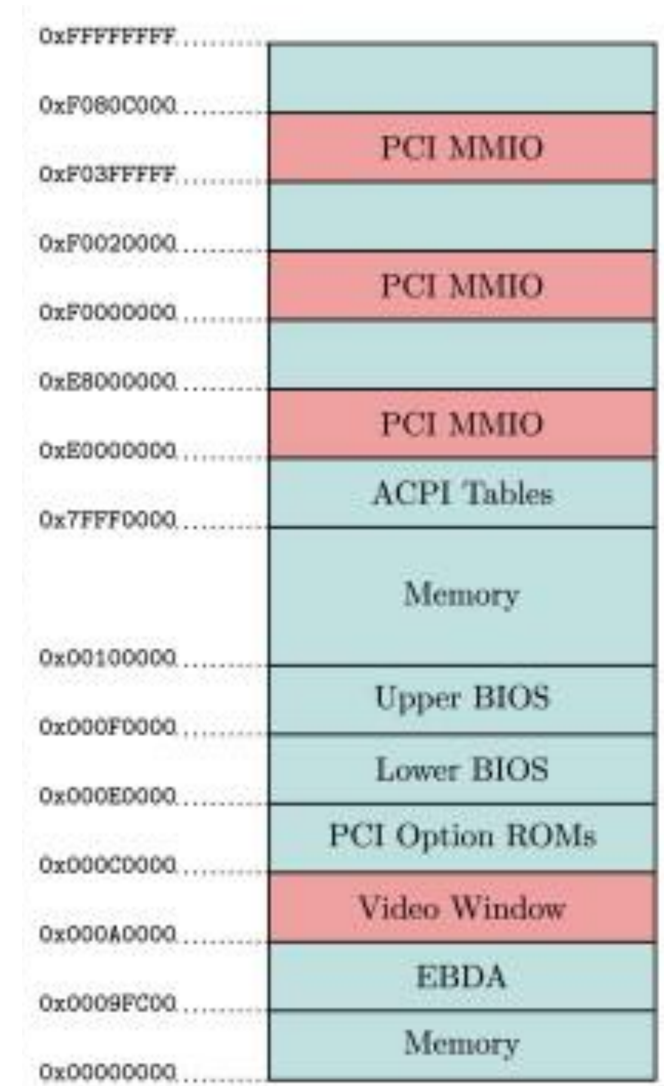
- Data structures **change among different OSs and OS versions**

- **Semantic Gap**: going from a raw sequence of bytes to high-level artifacts

Memory Acquisition

Memory Acquisition Internals

- **Physical address space is not continuous!**
  - **It contains physical RAM regions and other stuff...**
  - **# cat /proc/iomem** <- show the physical memory layout of the system
  - **Hardware peripherals map registers or parts of their integrated memory into the physical address space** via Memory Mapped I/O
  - **Any attempt to read the memory mapped to a device would probably crash the system**
- **Some parts of the RAM contain encrypted data or fundamental code needed for the system** (e.g, Intel SGX, UEFI code, SMRAM...)



Memory Acquisition

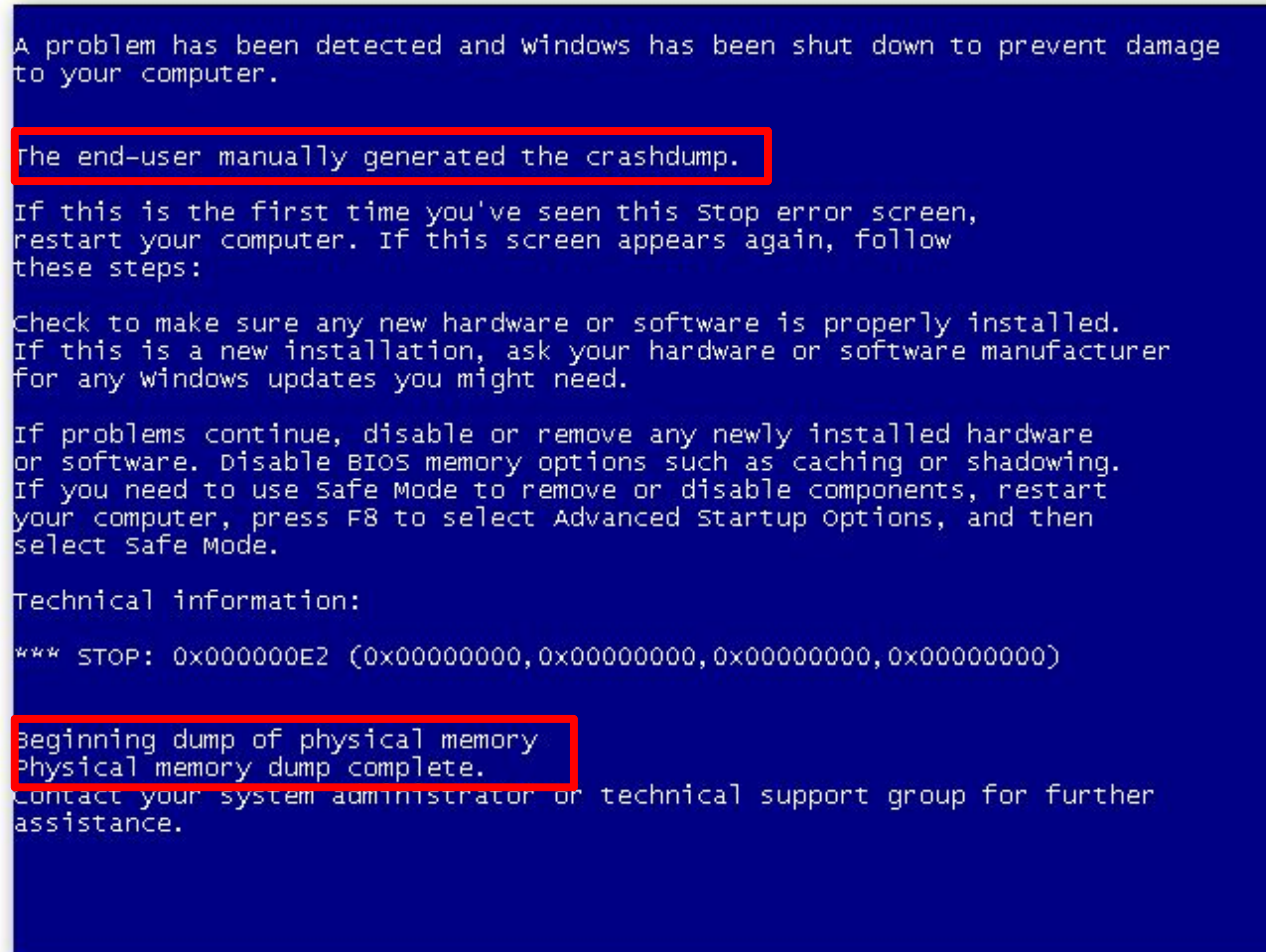
- **Software Acquisition**
  - **Relies on a program running** inside the system to read and store a copy of the memory
  - **The software is altering the system**, so its footprint is very important
- **Hardware Acquisition**
  - **Relies on hardware devices** to read the memory, often bypassing the CPU
  - **It does not introduce any new artifact** in the system
- **Most of the existing approaches don't freeze the system during the acquisition**, potentially (often!) leading to inconsistencies
- **Special case: Virtual machines**
  - If the analyst has access to the hypervisor **it is possible to perform an atomic dump**
  - **New technologies** like AMD Secure Encrypted Virtualization **can block any type of memory dump from the hypervisor**

Software Acquisition

- **Pseudo-device files**
  - **A file-like device** that can be copied using dd
  - **/dev/mem** and **/dev/kmem** in Linux
    - Access to user- and kernel-memory
    - **Not available on recent systems**
  - **\\.\PhysicalMemory** in Windows
    - **Not accessible from user space since Windows 2003 SP1**
- **Kernel-mode drivers**
  - exist to **overcome the previous limitations**
  - on modern systems **with Secure Boot enabled a signed driver is required**
- **Special tools**
  - acquire memory from **special CPU modes/special code regions** (e.g., SMM mode, IPMI controllers, Intel ME, UEFI code,...)

Crash Dumps

- **Windows can be configured to create a full memory dump in response to a Blue Screen of Death (BSoD)**
  - Dumps are **created in the swap area** and then **copied to regular files** at the next boot
  - Memory dumps can be forced by pressing **CTRL + Scroll Lock (x2)**
- <u>**Very accurate**</u>
  - **the system is frozen while the dump is taken**, allowing to take an atomic snapshot
- **Impact on disk analysis**
  - several GB are written to the disk, possibly overwriting other evidence
- **Hard to deploy:**
  - several configuration options that need to be set in advance in the registry or a system reboot



Hibernation Files

- **When the OS is hibernated** (suspended to disk) **a copy of the RAM is stored in a file** (hiberfil.sys in Windows, swap partition in Linux)

- If hibernation is supported, this is a **good method to obtain a memory dump**, with few limitations (e.g., it works in 64-bit architecture with more than 4GB or RAM)

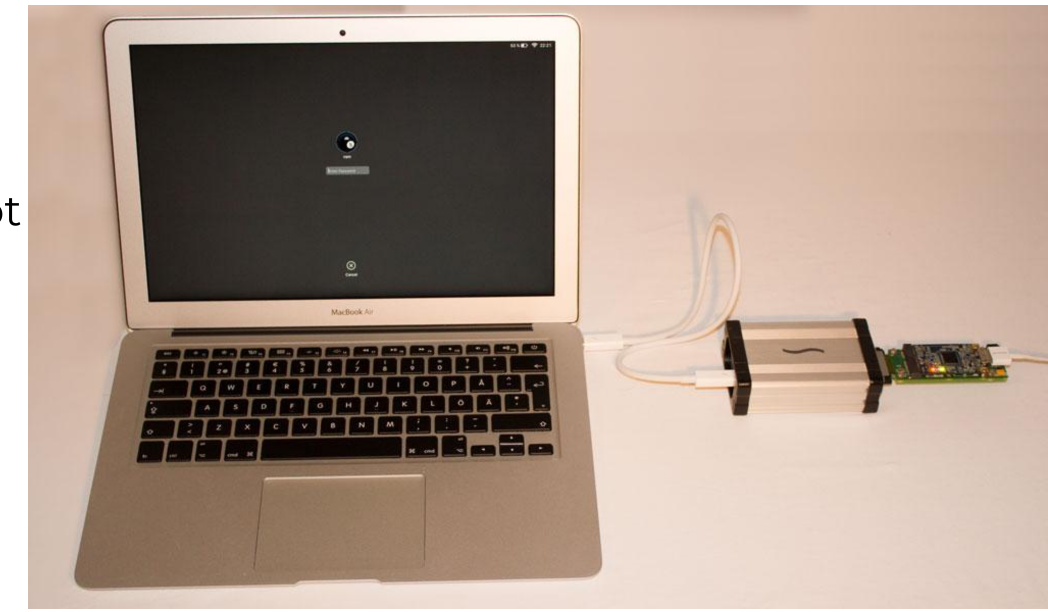
Tools

- **winpmem**
  - Supports **Windows XP SP2 to Windows 10**
  - Outputs **raw dumps or AFF4 dumps**
    (an archive that can contain multiple streams and additional information)
  - A version for Mac OS is also available (**OSXPmem**) and for Linux (**linpmem**)

- **LiME**
  - **Linux kernel module**
  - Outputs **raw dumps or LiME dumps**
  - Permits to **save dumps on external disk or send it through the network**

Hardware Acquisition

- **Based on DMA transfer on an external bus**
  - requires to have that bus on the motherboard, have access to it, and some security features not enabled (e.g, IOMMU)
  - **Not forensically sound**



- **Firewire**
  - **Directly access the main memory from a FireWire device**
  - Not common, no more used

- **PCI-Express**
  - **PCILeech, FPGA**
  - **Internal acquisition cards** which need to be connected to the bus **before** the incident

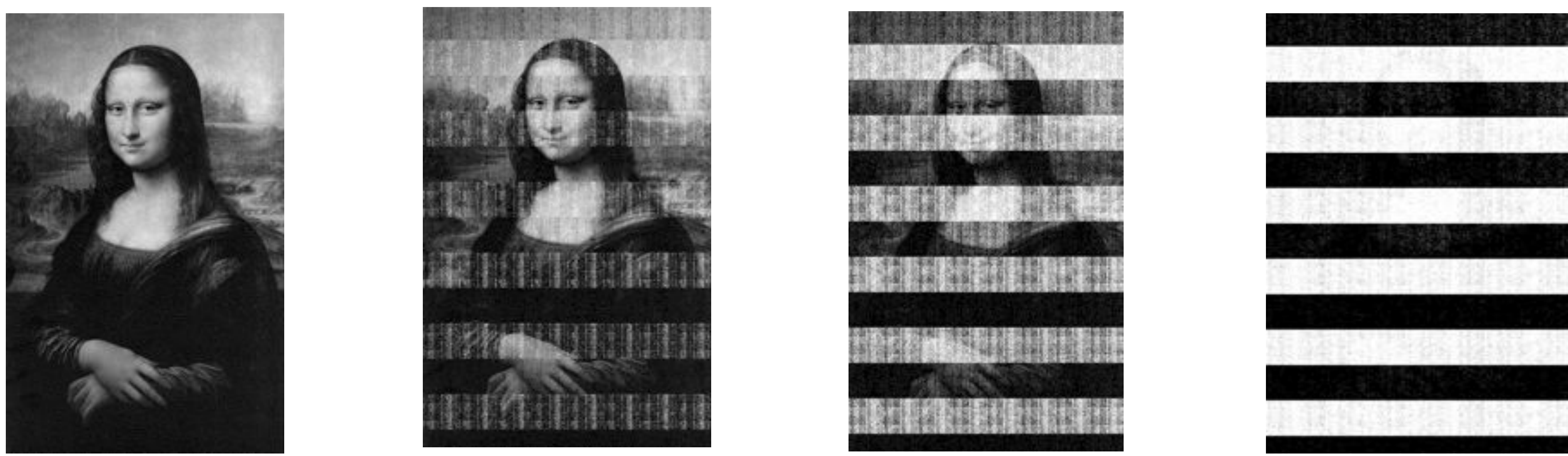
- **Thunderbolt / USB 4**

- **Intel DCI** (on Intel CPUs only) **/ JTAG**

Cold Boot Attack

- **Main memory is normally stored in DRAM chips**
  - **Information is stored in a capacitor, whose charge needs to be refreshed** every few milliseconds (or the charge would decay to the ground state)
  - **If not refreshed, the content of DRAM is completely lost** after several seconds (the actual time depends on the machine)
  - <u>**RAM is not zeroed at reboot!**</u>
- **Acquisition**:
  - **Cut the power** of the target machine
  - **Boot from network or from a USB drive**
  - **Copy the RAM** – the process is relatively fast (~30 sec per GB over the network to 4 min over USB)
  - **On modern systems with UEFI** this technique is **no more a viable option** (due to MOR bit protection)
  - **But what if the computer is not configured to boot from network or USB?**

Memory Degradation at Room Temperature



After: **5 seconds** **30 seconds** **60 seconds** **5 minutes**

Mona Lisa on the Rocks

- A multi-purpose “canned air” duster spray canister, held upside-down, discharges **very cold liquid refrigerant** instead of gas
- It can be used as a fast and cheap refrigerant for memory chips :)
- **1% of bits decayed after 10 minutes**

- **Drop it in a liquid nitrogen can**, and information is preserved unchanged for hours

0.17% bits decayed in 60 min

On the Practicability of Cold Boot Attacks

- The attack was originally **designed for DDR1 and DDR2**

- **On DDR3, the memory controller scrambles the data before writing it** to memory to reduce electromagnetic interference
  - Intel uses a Linear-feedback shift registers that can be reverted if a small plaintext is known
  - See **“Lest we forget: Cold-boot attacks on scrambled DDR3 memory”** (DFRWS EU 2016) for more information

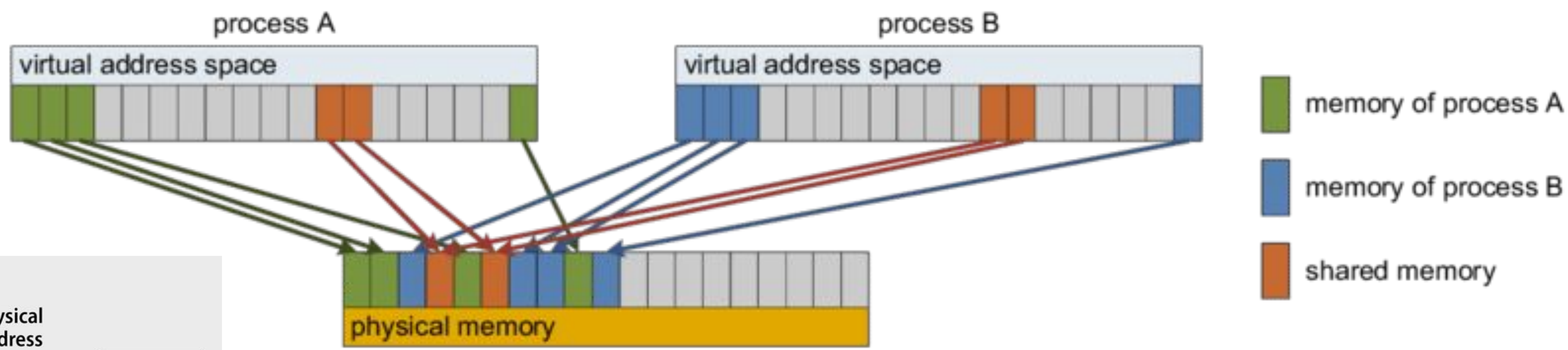
Memory Acquisition: RESUME

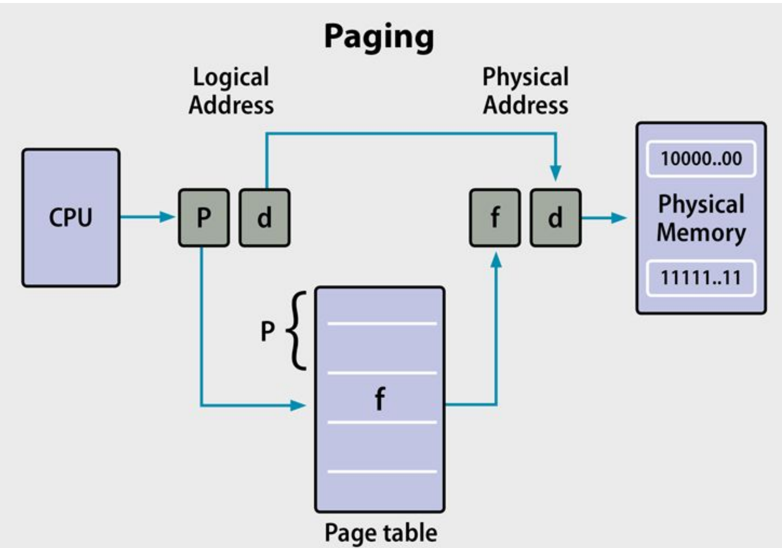
- **Software Acquisition**
  - **Easy method but... software alters the system**
- **Hardware Acquisition**
  - **Does not introduce new artifacts but.. relies on hardware devices**
- **Best case: Virtual machines** (without AMD SEV!)
  - **Fast, easy atomic dump**

Memory Analysis

Address Translation

- **Each process lives in a (quasi) separated Virtual Address Space**
- The virtual memory system stores the **mapping between virtual and physical addresses inside Page Tables**
- **The actual address translation depends on the CPU architecture and on certain CPU registers**





Memory Dump

Strings

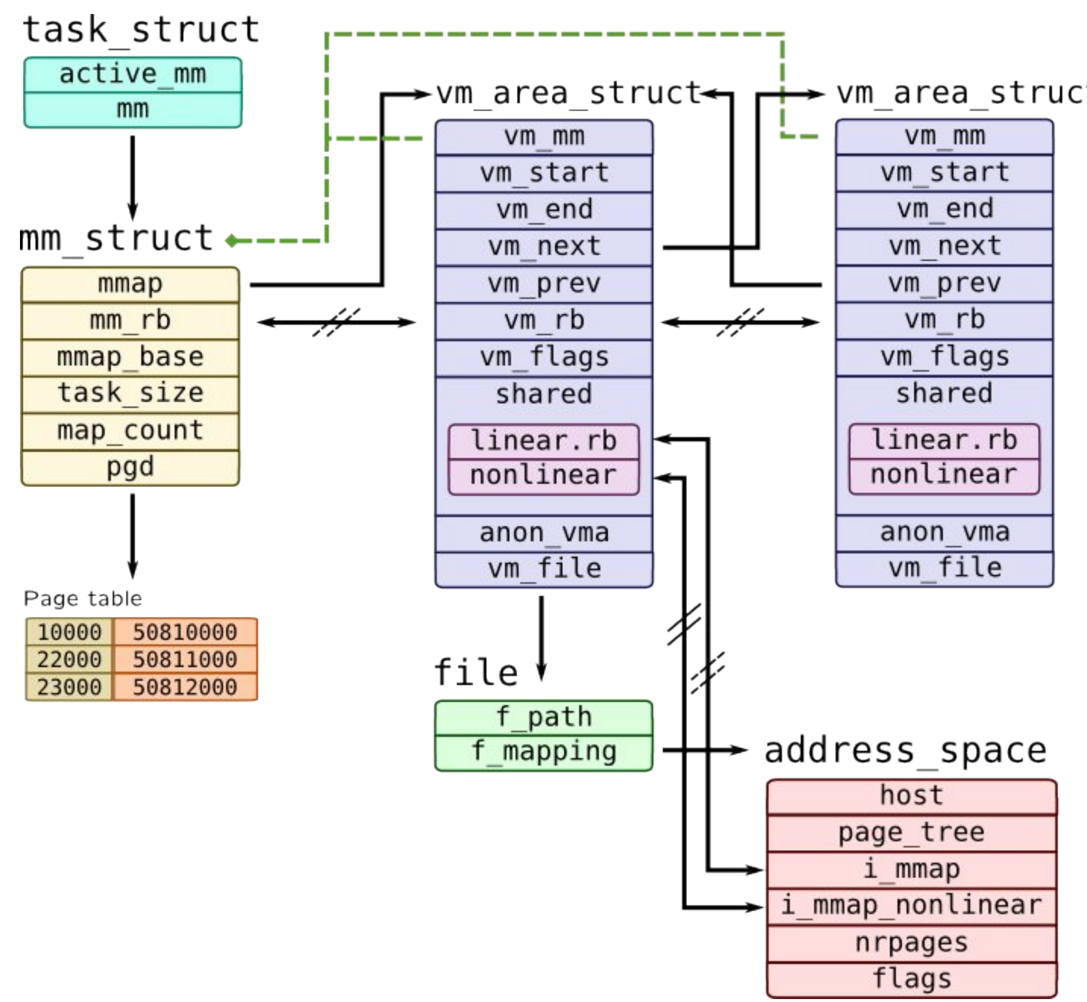
- A freshly booted machine roughly generates ~100MB of strings per GB of RAM*
  - ~580.000 strings of length 5
  - ~66.000 Unicode strings of length 5
- Starting notepad and IDA adds another ~7.000 new Unicode strings !!

⇒ **Much better to focus on something in particular (IP addresses, email headers, …)**

*Post-Mortem RAM Forensics – Tim Vidas 2007

Locating Structures

- **Fixed offsets**
  - Useful to find the kernel base image
- **Data structure traversal** (list walking, tree climbing, …)
  - **Extract allocated data structures**
  - **Requires knowledge of the kernel internals**
- **Linear scanning**
  - Search the memory for known patterns
  - It can detects de-allocated structures
  - **Requires knowledge of the kernel internals**
  - Fields validation to reduce false positives
    - Permitted values
    - Pointers target



Problems

- The modeling and extraction tools need a **very precise definition of the kernel structures**

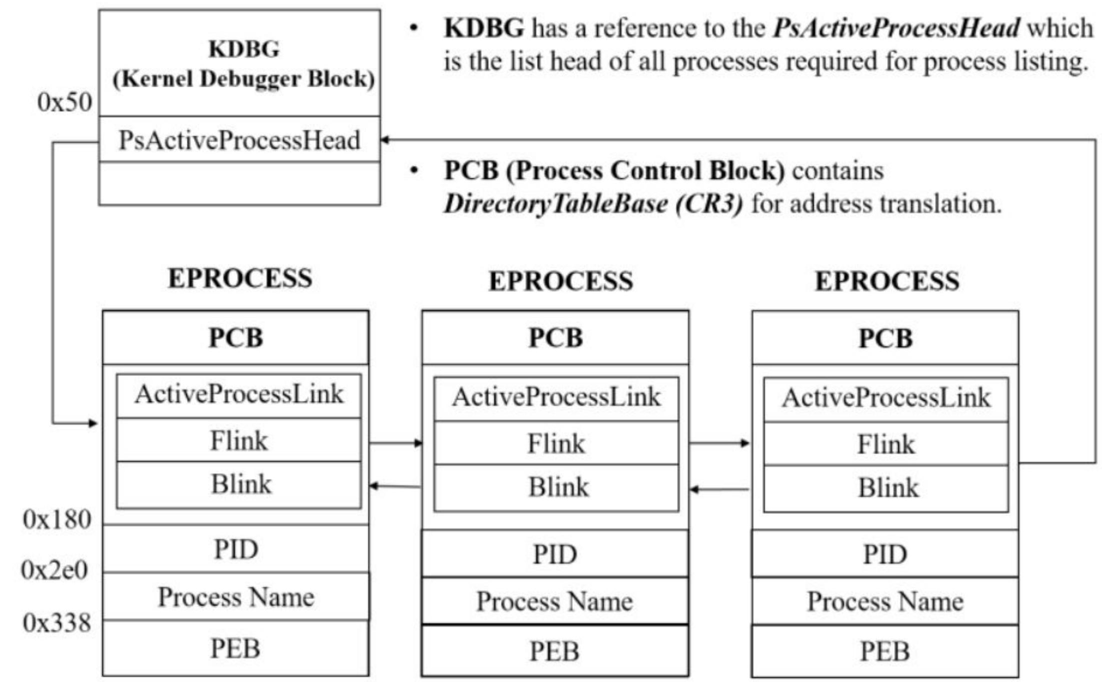
- But **kernel structures change quite rapidly and they are often unknown**
  - **In Windows, source code are not always available** for documentation
  - **In Linux, users can** install different kernel, apply patches, or **recompile the kernel** from scratch
  - **In general a deep knowledge of the kernel internals is required**

- **⇒ We need a <u>profile</u>: for each operating system, and each version of it we need a description and location of all the kernel data structures necessary to perform the analysis!**

Interesting Structures

(from now on, we are talking about Windows)

- **Each process is identified by** an Executive Process Block (**EPROCESS**)
- **All the EPROCESS are connected in a double linked list** (EPROCESS→ActiveProcessLinks→flink/blink)
    - Processes are **removed from the list when they exit**
    - **Rootkits often hide processes** by taking them out of the linked list
- **The EPROCESS structure contains a link to the Process Environment Block (PEB)** located in the process address space



Interesting Info

- **Eprocess**
  - **Creation and Exit time**
  - **Process ID and parent Process ID** (who started the process)
  - **Pointer to the handle table**
  - **Virtual Address Space descriptors** (VAD)
- **PEB**
  - Pointer to the **image base address**
    (where you can find the executable image)
  - Pointer to the **process parameters structure**
    (full path of binary, DLLs, and command line used to start the executable)
  - Pointer to the **DLLs loaded** by the process
    (three lists, ordered by loading time, initialization time, and memory address)
  - **Heap size** information
    (the pointer to the heap is located just after the PEB structure)

Kernel Global Variables

- A number of **hidden kernel variables are extremely helpful** to examine the state of the running system
  - **PsActiveProcessHead** points to the start of the kernel's list of **EPROCESS structures**
  - **PsLoadedModuleList** points to the list of currently **loaded kernel modules**
  - **HandleTableListHead** points to the head of list of **handle tables** (resources used by each process)
  - **MmPfnDatabase** is an array of structures describing each **physical page in the system**

Locating Kernel Variables

- The **variables are always at a fixed location** in memory
  - But unfortunately the **location changes between Windows versions**, patch levels, and even single hotfixes

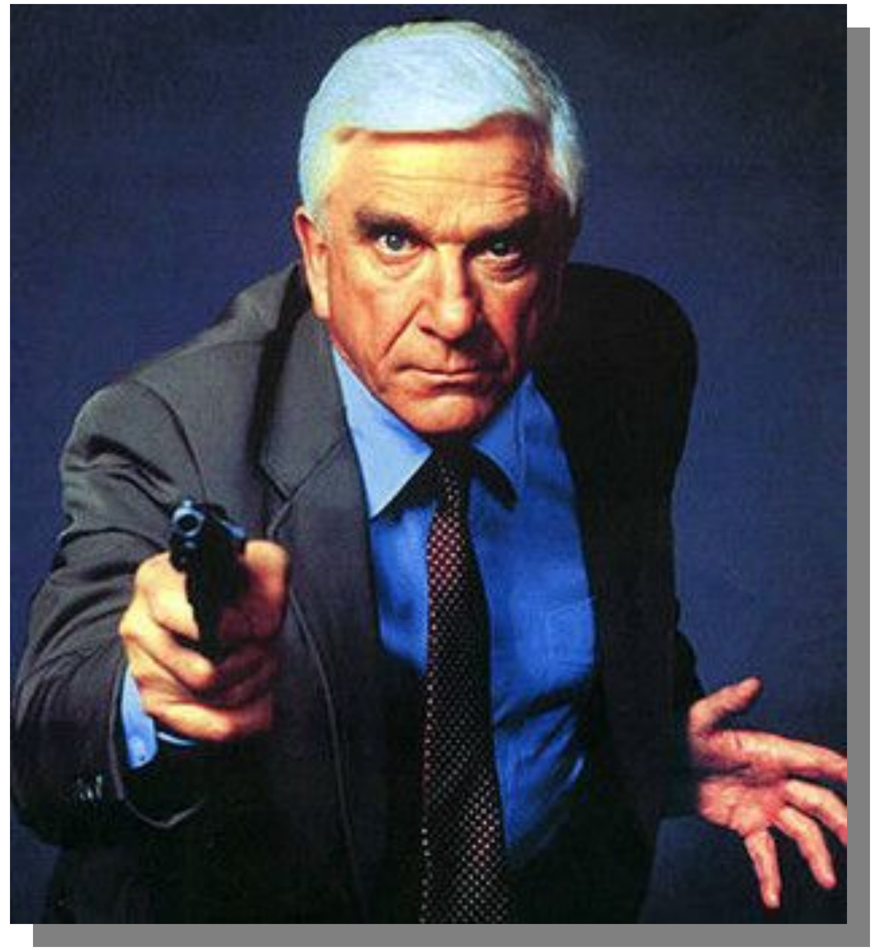
- **Windows keep a structure (_KDDEBUGGER_DATA64) for debugging purposes**, that contains the memory address of dozens of global kernel variables
  - In Windows {XP, 2003, Vista} **this structure can be found through a KPCR structure** that is located at a fixed address in memory
  - In Windows 2000, the structure has to be located by scanning the memory
  - **Windows 8 encodes the KDBG block making memory analysis more difficult**

Volatility

- **Open source memory analysis framework written in Python**
- **Supports**:
  - 32-bit and 64-bit **Windows OSs**
  - **Linux** 32 and 64-bit
  - **macOS**
  - **FreeBSD**
  - **Android**
- Volatility supports **raw dumps, crash dump, virtual machine snapshots, and hibernation files**

Volatility Plugins

- **Collection of tools** implemented as plugins
- **Plugins are just Python scripts** and can be easily installed by copying them into the plugin directory
  - The current version contains ~50 profiles and ~265 plugins
  - **A few** plugins have been developed **specifically to find signs of malware infections**
  - **Additional** (more research-oriented) plugins implemented by **Brendan Dolan-Gavitt**
    - http://www.cc.gatech.edu/~brendan/volatility/
  - Volatility plugins **developed and maintained by the community**:
    - https://github.com/volatilityfoundation/community
- **$ vol.py --info → list the available plugins**



Catching the bad Guys

Starting the memory analysis

- Suppose **you have received a memory dump** of a machine which performs suspected activity... **How to perform a memory analysis?**
    - The analysis often **starts** by listing and **investigating the processes that were running in the system**
        - **Open files, loaded DLLs, or network sockets** can help identifying suspicious cases
        - **The starting point for the analysis may come from another source** (e.g., a network sensor detected a suspicious connection)
    - The analysis also includes the **inspection of the kernel, to locate malicious kernel modules**
    - The analysis may end when you locate a known malicious file, or dump an unknown suspicious file that **require some further binary analysis**

Image Identification

```
andrea@ubuntu-20:~/volatility$ ./vol.py -f ~/Downloads/[redacted]vmem --profile=WinXPSP3x86 imageinfo
Volatility Foundation Volatility Framework 2.6.1
INFO    : volatility.debug    : Determining profile based on KDBG search...
          Suggested Profile(s) : WinXPSP2x86, WinXPSP3x86
                     AS Layer1 : IA32PagedMemoryPae (Kernel AS)
                     AS Layer2 : FileAddressSpace (/home/andrea/Downloads/[redacted].vmem)
                      PAE type : PAE
                           DTB : 0x319000L
                          KDBG : 0x80545ae0L
          Number of Processors : 1
     Image Type (Service Pack) : 3
                KPCR for CPU 0 : 0xffdff000L
             KUSER_SHARED_DATA : 0xffdf0000L
           Image date and time : 2011-06-03 04:31:36 UTC+0000
     Image local date and time : 2011-06-03 00:31:36 -0400
```

Detecting Malicious Processes

Hidden through DKOM (Direct Kernel Object Manipulation), by **removing the process from the EProcess linked list or disguised by renaming the process** to match a system or innocuous one

- **Compare the output of the plist and pscan plugins**
- **Psxview** outputs the list of process extracted in six different ways

List of Processes

```
andrea@ubuntu-20:~/volatility$ ./vol.py -f ~/Downloads/[redacted]vmem --profile=WinXPSP3x86 pslist
Volatility Foundation Volatility Framework 2.6.1
Offset(V)  Name                    PID   PPID   Thds     Hnds   Sess  Wow64 Start
---------- -------------------- ------ ------ ------ -------- ------ ------ ------------------------------
0x823c8830 System                    4      0     59      403 ------      0
0x820df020 smss.exe                376      4      3       19 ------      0 2010-10-29 17:08:53 UTC+0000
0x821a2da0 csrss.exe               600    376     11      395      0      0 2010-10-29 17:08:54 UTC+0000
0x81da5650 winlogon.exe            624    376     19      570      0      0 2010-10-29 17:08:54 UTC+0000
0x82073020 services.exe            668    624     21      431      0      0 2010-10-29 17:08:54 UTC+0000
0x81e70020 lsass.exe               680    624     19      342      0      0 2010-10-29 17:08:54 UTC+0000
0x823315d8 vmacthlp.exe            844    668      1       25      0      0 2010-10-29 17:08:55 UTC+0000
0x81fc5da0 VMwareTray.exe         1912   1196      1       50      0      0 2010-10-29 17:11:50 UTC+0000
0x81e6b660 VMwareUser.exe         1356   1196      9      251      0      0 2010-10-29 17:11:50 UTC+0000
0x8210d478 jusched.exe            1712   1196      1       26      0      0 2010-10-29 17:11:50 UTC+0000
0x82279998 imapi.exe               756    668      4      116      0      0 2010-10-29 17:11:54 UTC+0000
0x822b9a10 wuauclt.exe             976   1032      3      133      0      0 2010-10-29 17:12:03 UTC+0000
0x81c543a0 Procmon.exe             660   1196     13      189      0      0 2011-06-03 04:25:56 UTC+0000
0x81fa5390 wmiprvse.exe           1872    856      5      134      0      0 2011-06-03 04:25:58 UTC+0000
0x81c498c8 lsass.exe               868    668      2       23      0      0 2011-06-03 04:26:55 UTC+0000
0x81c47c00 lsass.exe              1928    668      4       65      0      0 2011-06-03 04:26:55 UTC+0000
0x81c0cda0 cmd.exe                 968   1664      0 --------      0      0 2011-06-03 04:31:35 UTC+0000
```

List of Processes

```
andrea@ubuntu-20:~/volatility$ ./vol.py -f ~/Downloads/[redacted]vmem --profile=WinXPSP3x86 pslist
Volatility Foundation Volatility Framework 2.6.1
Offset(V)  Name                    PID   PPID   Thds     Hnds   Sess  Wow64 Start
---------- -------------------- ------ ------ ------ -------- ------ ------ ------------------------------
0x823c8830 System                    4      0     59      403 ------      0
0x820df020 smss.exe                376      4      3       19 ------      0 2010-10-29 17:08:53 UTC+0000
0x821a2da0 csrss.exe               600    376     11      395      0      0 2010-10-29 17:08:54 UTC+0000
0x81da5650 winlogon.exe            624    376     19      570      0      0 2010-10-29 17:08:54 UTC+0000
0x82073020 services.exe            668    624     21      431      0      0 2010-10-29 17:08:54 UTC+0000
0x81e70020 lsass.exe               680    624     19      342      0      0 2010-10-29 17:08:54 UTC+0000
0x823315d8 vmacthlp.exe            844    668      1       25      0      0 2010-10-29 17:08:55 UTC+0000
0x81fc5da0 VMwareTray.exe         1912   1196      1       50      0      0 2010-10-29 17:11:50 UTC+0000
0x81e6b660 VMwareUser.exe         1356   1196      9      251      0      0 2010-10-29 17:11:50 UTC+0000
0x8210d478 jusched.exe            1712   1196      1       26      0      0 2010-10-29 17:11:50 UTC+0000
0x82279998 imapi.exe               756    668      4      116      0      0 2010-10-29 17:11:54 UTC+0000
0x822b9a10 wuauclt.exe             976   1032      3      133      0      0 2010-10-29 17:12:03 UTC+0000
0x81c543a0 Procmon.exe             660   1196     13      189      0      0 2011-06-03 04:25:56 UTC+0000
0x81fa5390 wmiprvse.exe           1872    856      5      134      0      0 2011-06-03 04:25:58 UTC+0000
0x81c498c8 lsass.exe               868    668      2       23      0      0 2011-06-03 04:26:55 UTC+0000
0x81c47c00 lsass.exe              1928    668      4       65      0      0 2011-06-03 04:26:55 UTC+0000
0x81c0cda0 cmd.exe                 968   1664      0 --------      0      0 2011-06-03 04:31:35 UTC+0000
```

LSASS a.k.a. Local Security Authentication Subsystem Service

- Responsible for **authenticating users**
- **Only <u>one</u> per system** 🔥
- Associated with **Local System Account**
- **Parent process: winlogon.exe**
- Executable in **%SystemRoot%\System32\lsass.exe**
- **Starts within seconds of boot times**

Process SIDs

```
andrea@ubuntu-20:~/volatility$ ./vol.py -f ~/Downloads/[redacted]vmem --profile=WinXPSP3x86 getsids -p 680,868,1928
Volatility Foundation Volatility Framework 2.6.1
lsass.exe (680): S-1-5-18 (Local System)
lsass.exe (680): S-1-5-32-544 (Administrators)
lsass.exe (680): S-1-1-0 (Everyone)
lsass.exe (680): S-1-5-11 (Authenticated Users)
lsass.exe (868): S-1-5-18 (Local System)
lsass.exe (868): S-1-5-32-544 (Administrators)
lsass.exe (868): S-1-1-0 (Everyone)
lsass.exe (868): S-1-5-11 (Authenticated Users)
lsass.exe (1928): S-1-5-18 (Local System)
lsass.exe (1928): S-1-5-32-544 (Administrators)
lsass.exe (1928): S-1-1-0 (Everyone)
lsass.exe (1928): S-1-5-11 (Authenticated Users)
```

LSASS a.k.a. Local Security Authentication Subsystem Service

- Responsible for **authenticating users**
- **Only <u>one</u> per system** 🔥
- Associated with **Local System Account** ✅
- **Parent process: winlogon.exe**
- Executable in **%SystemRoot%\System32\lsass.exe**
- **Starts within seconds of boot times**

Process parents

```
andrea@ubuntu-20:~/volatility$ ./vol.py -f ~/Downloads/[redacted]vmem --profile=WinXPSP3x86 pslist
Volatility Foundation Volatility Framework 2.6.1
Offset(V)  Name                    PID   PPID   Thds     Hnds   Sess  Wow64 Start
---------- -------------------- ------ ------ ------ -------- ------ ------ ------------------------------
0x823c8830 System                    4      0     59      403 ------      0
0x820df020 smss.exe                376      4      3       19 ------      0 2010-10-29 17:08:53 UTC+0000
0x821a2da0 csrss.exe               600    376     11      395      0      0 2010-10-29 17:08:54 UTC+0000
0x81da5650 winlogon.exe            624    376     19      570      0      0 2010-10-29 17:08:54 UTC+0000
0x82073020 services.exe            668    624     21      431      0      0 2010-10-29 17:08:54 UTC+0000
0x81e70020 lsass.exe               680    624     19      342      0      0 2010-10-29 17:08:54 UTC+0000
0x823315d8 vmacthlp.exe            844    668      1       25      0      0 2010-10-29 17:08:55 UTC+0000
0x81fc5da0 VMwareTray.exe         1912   1196      1       50      0      0 2010-10-29 17:11:50 UTC+0000
0x81e6b660 VMwareUser.exe         1356   1196      9      251      0      0 2010-10-29 17:11:50 UTC+0000
0x8210d478 jusched.exe            1712   1196      1       26      0      0 2010-10-29 17:11:50 UTC+0000
0x82279998 imapi.exe               756    668      4      116      0      0 2010-10-29 17:11:54 UTC+0000
0x822b9a10 wuauclt.exe             976   1032      3      133      0      0 2010-10-29 17:12:03 UTC+0000
0x81c543a0 Procmon.exe             660   1196     13      189      0      0 2011-06-03 04:25:56 UTC+0000
0x81fa5390 wmiprvse.exe           1872    856      5      134      0      0 2011-06-03 04:25:58 UTC+0000
0x81c498c8 lsass.exe               868    668      2       23      0      0 2011-06-03 04:26:55 UTC+0000
0x81c47c00 lsass.exe              1928    668      4       65      0      0 2011-06-03 04:26:55 UTC+0000
0x81c0cda0 cmd.exe                 968   1664      0 --------      0      0 2011-06-03 04:31:35 UTC+0000
```

LSASS a.k.a. Local Security Authentication Subsystem Service

- Responsible for **authenticating users**
- **Only <u>one</u> per system** 🔥
- Associated with **Local System Account** ✅
- **Parent process: winlogon.exe** 🔥
- Executable in **%SystemRoot%\System32\lsass.exe**
- **Starts within seconds of boot times**

Start Time

```
andrea@ubuntu-20:~/volatility$ ./vol.py -f ~/Downloads/[redacted]vmem --profile=WinXPSP3x86 pslist
Volatility Foundation Volatility Framework 2.6.1
Offset(V)  Name                    PID   PPID   Thds     Hnds   Sess  Wow64 Start
---------- -------------------- ------ ------ ------ -------- ------ ------ ------------------------------
0x823c8830 System                    4      0     59      403 ------      0
0x820df020 smss.exe                376      4      3       19 ------      0 2010-10-29 17:08:53 UTC+0000
0x821a2da0 csrss.exe               600    376     11      395      0      0 2010-10-29 17:08:54 UTC+0000
0x81da5650 winlogon.exe            624    376     19      570      0      0 2010-10-29 17:08:54 UTC+0000
0x82073020 services.exe            668    624     21      431      0      0 2010-10-29 17:08:54 UTC+0000
0x81e70020 lsass.exe               680    624     19      342      0      0 2010-10-29 17:08:54 UTC+0000
0x823315d8 vmacthlp.exe            844    668      1       25      0      0 2010-10-29 17:08:55 UTC+0000
0x81fc5da0 VMwareTray.exe         1912   1196      1       50      0      0 2010-10-29 17:11:50 UTC+0000
0x81e6b660 VMwareUser.exe         1356   1196      9      251      0      0 2010-10-29 17:11:50 UTC+0000
0x8210d478 jusched.exe            1712   1196      1       26      0      0 2010-10-29 17:11:50 UTC+0000
0x82279998 imapi.exe               756    668      4      116      0      0 2010-10-29 17:11:54 UTC+0000
0x822b9a10 wuauclt.exe             976   1032      3      133      0      0 2010-10-29 17:12:03 UTC+0000
0x81c543a0 Procmon.exe             660   1196     13      189      0      0 2011-06-03 04:25:56 UTC+0000
0x81fa5390 wmiprvse.exe           1872    856      5      134      0      0 2011-06-03 04:25:58 UTC+0000
0x81c498c8 lsass.exe               868    668      2       23      0      0 2011-06-03 04:26:55 UTC+0000
0x81c47c00 lsass.exe              1928    668      4       65      0      0 2011-06-03 04:26:55 UTC+0000
0x81c0cda0 cmd.exe                 968   1664      0 --------      0      0 2011-06-03 04:31:35 UTC+0000
```

LSASS a.k.a. Local Security Authentication Subsystem Service

- Responsible for **authenticating users**
- **Only <u>one</u> per system** 🔥
- Associated with **Local System Account** ✅
- **Parent process: winlogon.exe** 🔥
- Executable in **%SystemRoot%\System32\lsass.exe**
- **Starts within seconds of boot times** 🔥

Detecting Injected DLLs

Injecting a DLL inside another process is a very common way for malware to hide their presence by not showing up in the process list

- **Examine the VAD** for areas associated to DLLs
  - Even more **suspicious** if the **page** permissions are **RWE**
  - The **malfind plugin** is automatically searching for these cases
- Use **ldrmodules to detect unlinked DLLs** that are not listed

The missing DLL…

```
andrea@ubuntu-20:~/volatility$ ./vol.py -f ~/Downloads/[redacted]vmem --profile=WinXPSP3x86 ldrmodules -p 1928 -v
Volatility Foundation Volatility Framework 2.6.1
Pid      Process              Base       InLoad InInit InMem MappedPath
-------- -------------------- ---------- ------ ------ ----- ----------
    1928 lsass.exe            0x00080000 False  False  False
    1928 lsass.exe            0x7c900000 True   True   True  \WINDOWS\system32\ntdll.dll
  Load Path: C:\WINDOWS\system32\ntdll.dll : ntdll.dll
  Init Path: C:\WINDOWS\system32\ntdll.dll : ntdll.dll
  Mem Path:  C:\WINDOWS\system32\ntdll.dll : ntdll.dll
    1928 lsass.exe            0x00870000 True   True   True
  Load Path: C:\WINDOWS\system32\KERNEL32.DLL.ASLR.0360b7ab : KERNEL32.DLL.ASLR.0360b7ab
  Init Path: C:\WINDOWS\system32\KERNEL32.DLL.ASLR.0360b7ab : KERNEL32.DLL.ASLR.0360b7ab
  Mem Path:  C:\WINDOWS\system32\KERNEL32.DLL.ASLR.0360b7ab : KERNEL32.DLL.ASLR.0360b7ab
    1928 lsass.exe            0x76f20000 True   True   True  \WINDOWS\system32\dnsapi.dll
  Load Path: C:\WINDOWS\system32\DNSAPI.dll : DNSAPI.dll
  Init Path: C:\WINDOWS\system32\DNSAPI.dll : DNSAPI.dll
  Mem Path:  C:\WINDOWS\system32\DNSAPI.dll : DNSAPI.dll
```

Something in the clipboard

```
andrea@ubuntu-20:~/volatility$ ./vol.py -f ~/Downloads/[redacted].vmem --profile=WinXPSP3x86 clipboard
Volatility Foundation Volatility Framework 2.6.1
Session    WindowStation Format                  Handle Object     Data
---------- ------------- ------------------ ---------- ---------- --------------------------------------------------
         0 WinSta0       CF_UNICODETEXT       0x136012b 0xe29b0c68 74ddc49a7c121a61b8d06c03f92d0c13.exe
         0 WinSta0       CF_LOCALE             0x270101 0xe1bdab58
         0 WinSta0       CF_TEXT                    0x1 ----------
         0 WinSta0       CF_OEMTEXT                 0x1 ----------
```

Hidden services/kernel drivers...

```
andrea@ubuntu-20:~/volatility$ ./vol.py -f ~/Downloads/[redacted].vmem --profile=WinXPSP3x86 servicediff
Volatility Foundation Volatility Framework 2.6.1

Missing service      : MRxNet
Description          : (REG_SZ) MRXNET
DisplayName          : (REG_SZ) MRXNET
ErrorControl         : (REG_DWORD) 0
Group                : (REG_SZ) Network
ImagePath            : (REG_SZ) \??\C:\WINDOWS\system32\Drivers\mrxnet.sys
Start                : (REG_DWORD) 1
Type                 : (REG_DWORD) 1

Missing service      : MRxCls
Description          : (REG_SZ) MRXCLS
DisplayName          : (REG_SZ) MRXCLS
ErrorControl         : (REG_DWORD) 0
Group                : (REG_SZ) Network
ImagePath            : (REG_SZ) \??\C:\WINDOWS\system32\Drivers\mrxcls.sys
Start                : (REG_DWORD) 1
Type                 : (REG_DWORD) 1
```

And it was...

Full analysis here:
http://mnin.blogspot.com/2011/06/examining-stuxnets-footprint-in-memory.html

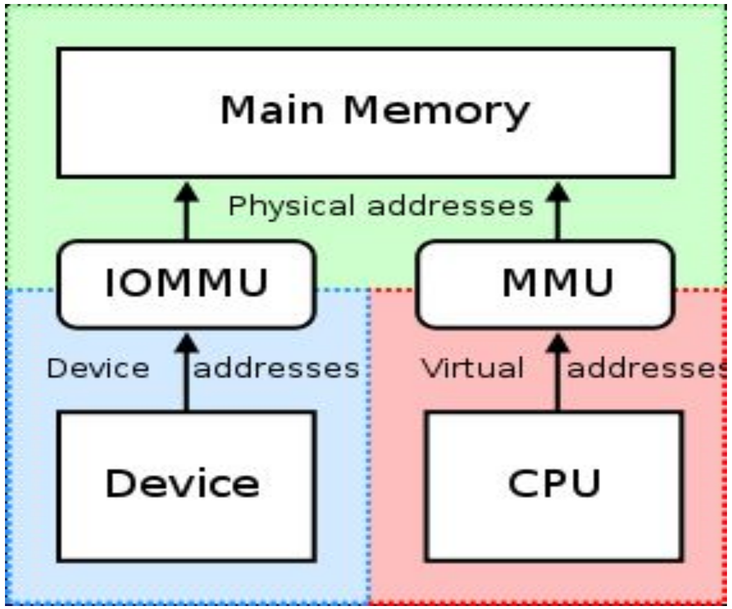
And now…

DEMO!

(on a toy Linux ransomware)

IOMMU

- The Input/output memory management unit (IOMMU) introduces **virtual memory for external devices**
- If properly configured, **it can be used to prevent certain devices to access some range of memory**
    - This is typically the case **when a hypervisor is running**
    - In this case, it is **very hard to get a physical image of the entire memory**
- **Malware can configure IOMMU to crash the system or returns false data** when read from external devices
    - **"Beyond The CPU: Defeating Hardware Based RAM Acquisition"**



(Very) Short Introduction to Address Translation

- **Memory analysis requires the ability to translate Virtual Addresses** used by programs **into the true memory locations** in the memory image
- **Memory is divided into pages** of 4KB each (in Intel architecture)
- **The OS presents to each program a large private virtual address space**
- Each time a program references a virtual address, the **MMU translates that virtual address into a physical location** and accesses the requested data
- **MMU uses data-structure managed by the kernel (page tables)** to perform automatic address translations