When Malware Changed Its Mind: An Empirical Study of Variable Program Behaviors in the Real World

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whoami

- **Erin Avllazagaj**
  - Phd Student @ University of Maryland, College Park
  - Data-driven analysis of malware in the wild

Agenda

- Drawbacks of dynamic analysis
- Measuring variability
- Finding invariants
  - Actionable implications
- Malware VS current dynamic analysis
  - Lessons learned

Malware Behavior Changes Across Environments

Malware Behavior Changes Across Environments

- Missing libraries, different language settings, etc.[1]

[1]

		Description of behavior
76.76 %	142	same behavior
9.19 %	17	evasion of Anubis
5.41 %	10	.NET environment required
3.24 %	6	evasion of our driver
3.24 %	6	different behavior due to other characteristics
2.16 %	4	not working in the German environment

[1] Lindorfer et al. "Detecting environment-sensitive malware." *RAID*, 2011.

Malware Behavior Changes Across Environments

- Missing libraries, different language settings, etc.[1]

- Prudent practices[2]:
  - "[…] caution generalizing from a single OS version […]"

[1]

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Malware Behavior Changes Across Environments

- Example: Ramnit Worm

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int __cdecl try_to_exploit(LPSTR lpCommandLine)
{
  if ( !is_win8() && !is_win8_1() )
  {
    if ( is_xp() )
    {
      if ( !check_updates_xp((int)"KB3000061") )
      {
        if ( is_admin() )
          return 1;
LABEL_6:
        execute_CVE_2014_4113(lpCommandLine);
        return 1;
      }
    }
    else if ( !check_updates_other((int)"KB3000061") )
    {
      if ( is_admin() && check_authority() > 1 )
        return 1;
      goto LABEL_6;
    }
    try_second_exploit(lpCommandLine);
    return 1;
  }
  return 0;
}
```

https://cert.pl/en/posts/2017/09/ramnit-in-depth-analysis/

Malware Behavior Changes Across Environments

- Example: Ramnit Worm
  - Exploits CVE-2013-3660
    - Line 22
    - Local Privilege escalation on Win 7
    - Creates hundreds of **mutexes**
      - until exploit succeeds

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- Example: Ramnit Worm
  - Exploits CVE-2013-3660
    - Line 22
    - Local Privilege escalation on Win 7
    - Creates hundreds of **mutexes**
      - until exploit succeeds
  - Only works on:
    - vulnerable OS versions
    - when run in **non-admin**

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Research Questions

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- What parts of the execution trace vary more? And by how much?

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RQ2: Invariant analysis in the wild

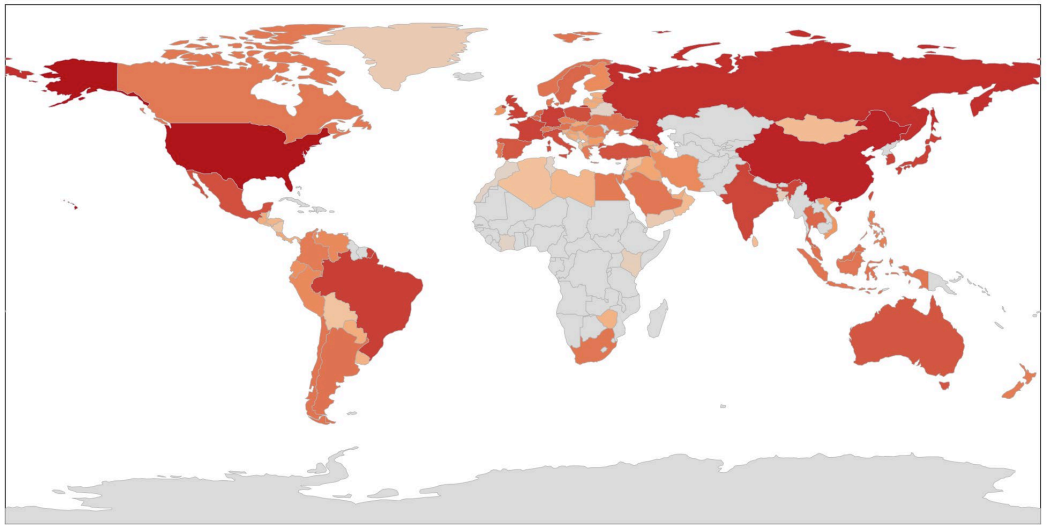
- Can we find behavioral invariants across executions?

RQ3: Impact of variability

- What is the impact of variability on malware detection and clustering?

The Dataset

- **7.6M** execution traces
- **5.4M** real users' machines in **>100 countries** in the world
- From **2018**



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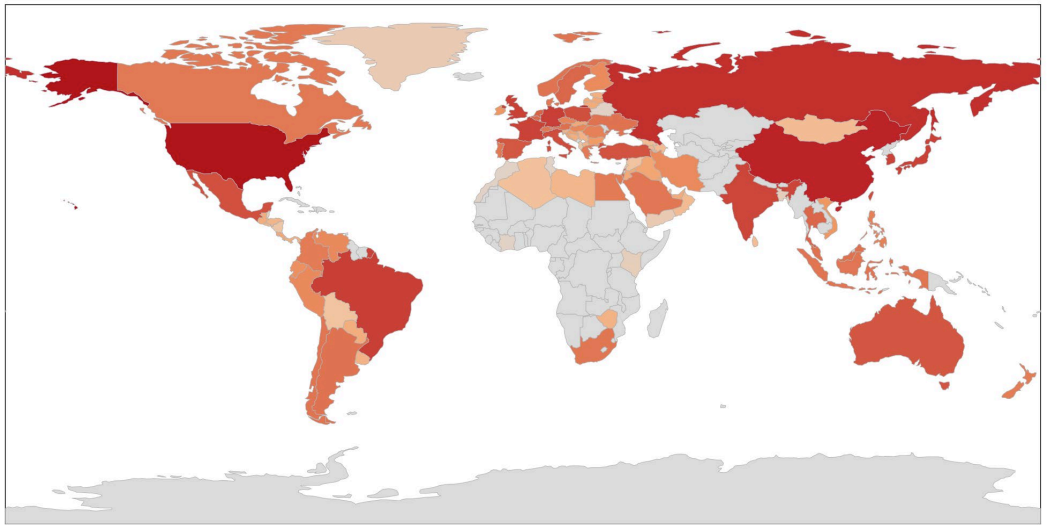
- From **2018**
- No private data is collected, passive recording



The Dataset (introduction)

Action type	File name	File path	…	sample Hash	Exec.id	Mach.id
File Create	setup.exe	CSIDL_PROFILE	…	AAA	1	abc
Mtx. Create	mtx!asjkf	-	…	ABC	5243523	abd
…	…	…	…	…	…	…

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Using VirusTotal labels and AVClass[1] (**2019**) we found:

22K benign, **2.4K** malware and **1.6K** PUP

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RQ1: Variability Analysis In The Wild

- Ramnit worm exploit

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RQ1: Variability Analysis In The Wild

- Ramnit worm exploit

- When this line is reached
  - ~100 more mutex create events
  - based on the **machine**

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RQ1: Variability Analysis In The Wild (machines)

Methodology

(for each hash)

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File Creations: 5
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...
Total: 52

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[45, … , **52** , … , **92** , … , 100] → IQR → 92 – 52 = **40**

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Analysis in the paper

[45, … , **52** , … , **92** , … , 100] → IQR → 92 – 52 = **40**

RQ1: Variability Analysis In The Wild (machines)

IQR → 92 – 52 = **40**

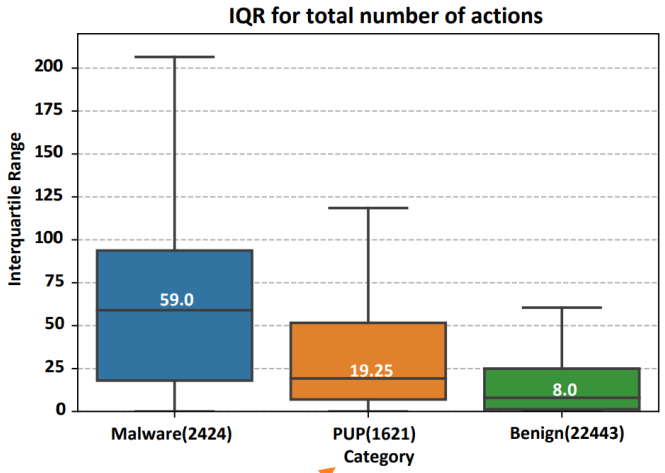
IQR → **10**

IQR → **0**

IQR → **100**

...

IQR → **60**



For all malware (blue boxplot)

For all PUP (orange boxplot)

...

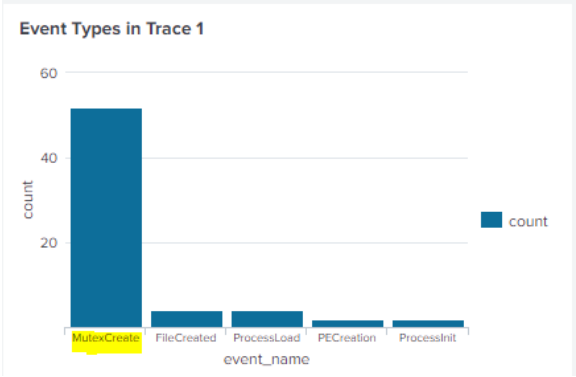
For all benign (green boxplot)

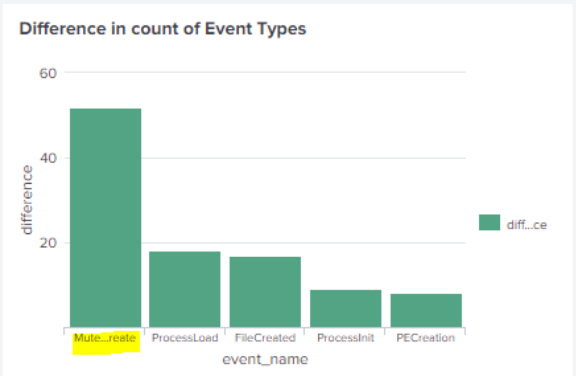
Back to Ramnit

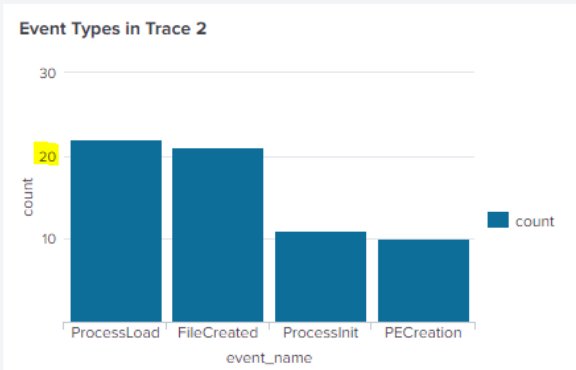
ne	server_date	local_time	platform_country_code	platform_processor	platform_system	enterprise_guid	machine_guid
31	Mon Oct 23 00:00:00 2018	Mon Oct 9 10:57:06 2018	55	x86 Family 6 Model 58 Stepping 9	Windows 7 build 7601 Service Pack 1	NULL	f6b4879ff52d11e6a55e94de80f65b84
20	Fri Nov 17 00:00:00 2018	Sun Nov 12 02:08:58 2018	86	Intel64 Family 6 Model 61 Stepping 4	Windows 10 Home China build 15063	NULL	f852fa3f06f64239b78ce5fd4ab77ec4

Trace 1

Trace 2





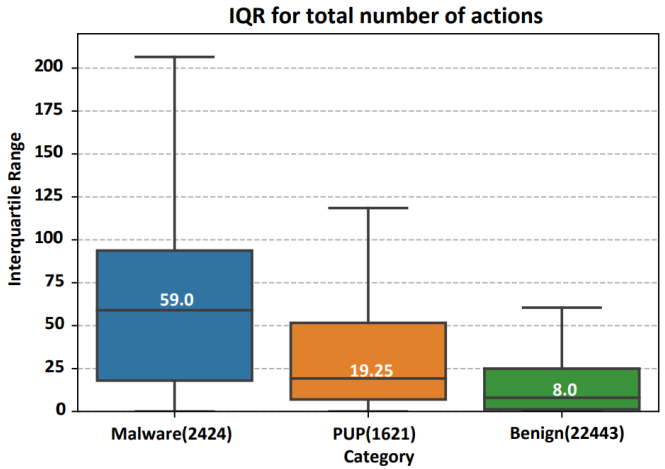


- Intuition
  - Trace 1 → vulnerable machine (and running in user mode)
  - Trace 2 → machine is not vulnerable (or running in Admin mode)

- IQR variability across machines will be large for Ramnit (sum of the green bars)

RQ1: Variability Analysis In The Wild (machines)

- At least 50% of the malware:
  - **59** missing or additional actions



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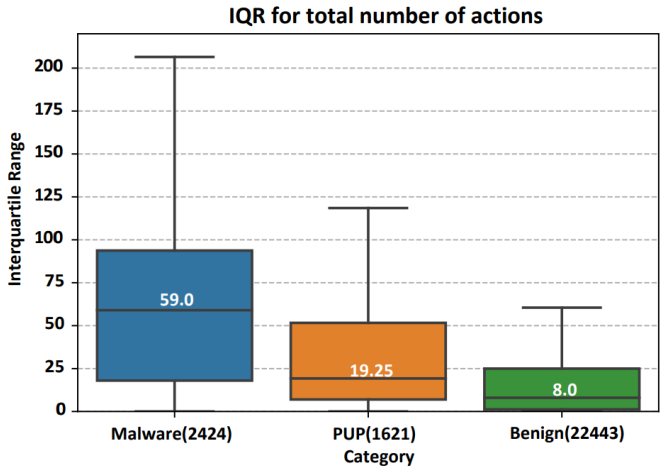
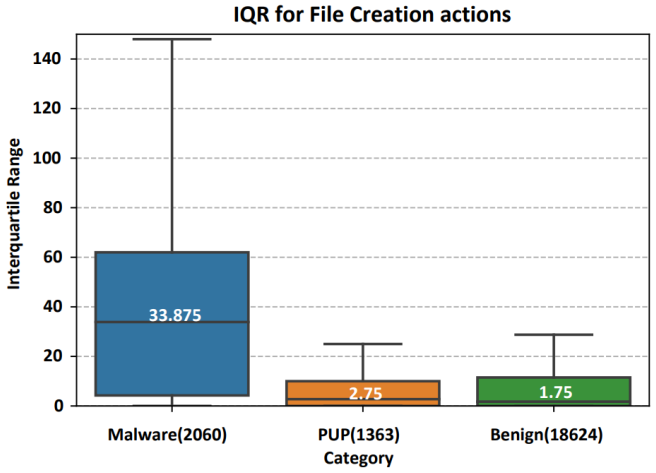


- File creation
  - The major source of machine-induced variability in malware.



RQ1: Variability Analysis In The Wild (machines)

- Methodology:
  - IQR of the number of unique parameter values across different machines.

- Number of unique file names varies by **25** across machines

		Median			75^{th} percentile		
		Mal	**PUP**	**Ben**	**Mal**	**PUP**	**Ben**
File	Path	4	1	-	10	3	2
	Name	25	2	1	49	8	8
	Ext.	3	1	-	5	2	1

Details in the paper

RQ1: Variability Analysis In The Wild (machines)

- Measuring parameter value overlap

Details in the paper

RQ1: Variability Analysis In The Wild (machines)

- Measuring parameter value overlap
  - No shared value across machines for ~99% of the samples.

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Details in the paper

RQ1: Case study (Gulpteba)

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  - 0 for file names
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- Mutexes were a better candidate for building signatures
  - `h48yorbq6rm87zot` → appeared in all the machines
  - `ZonesCacheCounterMutex` and `ZoneAttributeCacheCounterMutex` only appeared in half of the machines, which explains the IQR of 2

https://www.trendmicro.com/vinfo/us/threat-encyclopedia/search/trojanspy.win32.glupteba.a.

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  - `ZonesCacheCounterMutex` and `ZoneAttributeCacheCounterMutex` only appeared in half of the machines, which explains the IQR of 2
  - Confirmed by a report from TrendMicro[1]

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RQ1 Summary

- High variability in malware across machines
  - File Creation makes up most of variability in malware
  - File name is the most variable parameter
  - For most malware there isn't a single parameter value shared across all machines (except file extension)

RQ2: Invariant Analysis In The Wild

- Can we find an invariant to detect these malware?

RQ2: Invariant Analysis In The Wild

- Focus on action-parameter pair signatures
  - used in Sigma
    - SIEM rules

```
logsource:
    category: process_creation
    product: windows
detection:
    selection:
        CommandLine: '*-noni -ep bypass $*'
    condition: selection
```

https://github.com/SigmaHQ/sigma

RQ2: Invariant Analysis In The Wild

- Focus on action-parameter pair signatures
  - used in cuckoo
    - Suspicious activity

```
class CreatesUserFolderEXE(Signature):
    name = "creates_user_folder_exe"
    description = "Creates an executable file in a user folder"
    severity = 3
    families = ["persistance"]
    authors = ["Kevin Ross"]
    minimum = "2.0"
    ttp = ["T1129"]

    directories_re = [
        "^[a-zA-Z]:\\\\Users\\\\[^\\\\]+\\\\AppData\\\\.*",
        "^[a-zA-Z]:\\\\Documents\\ and\\ Settings\\\\[^\\\\]+\\\\Local\\ Settings\\\\.*",
    ]

    def on_complete(self):
        for dropped in self.get_results("dropped", []):
            if "filepath" in dropped:
                droppedtype = dropped["type"]
                filepath = dropped["filepath"]
                if "MS-DOS executable" in droppedtype:
                    for directory in self.directories_re:
                        if re.match(directory, filepath):
                            self.mark_ioc("file", filepath)

        return self.has_marks()
```

https://github.com/cuckoosandbox/community/tree/master/modules/signatures

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    def on_complete(self):
        for dropped in self.get_results("dropped", []):
            if "filepath" in dropped:
                droppedtype = dropped["type"]
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                if "MS-DOS executable" in droppedtype:
                    for directory in self.directories_re:
                        if re.match(directory, filepath):
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Prevalence of basic tokens

```yaml
title: Octopus Scanner Malware
id: 805c55d9-31e6-4846-9878-c34c75054fe9
status: experimental
description: Detects Octopus Scanner Malware.
references:
  - https://securitylab.github.com/research/octopus-scanner-malware-open-source-supply-chain
tags:
  - attack.t1195
  - attack.t1195.001
author: NVISO
date: 2020/06/09
logsource:
  product: windows
  category: file_event
detection:
  selection:
    TargetFilename|endswith:
      - '\AppData\Local\Microsoft\Cache134.dat'
      - '\AppData\Local\Microsoft\ExplorerSync.db'
  condition: selection
falsepositives:
  - Unknown
level: high
```

```yaml
logsource:
    category: registry_event
    product: windows
detection:
    selection:
        TargetObject:
            - 'HKCR\CLSID\{E08A0F4B-1F65-4D4D-9A09-BD4625B9C5A1}\Model'
        TargetObject|endswith:
              # covers HKU\* and HKLM..
            - '\SOFTWARE\App\AppXbf13d4ea2945444d8b13e2121cb6b663\Application'
            - '\SOFTWARE\App\AppXbf13d4ea2945444d8b13e2121cb6b663\DefaultIcon'
            - '\SOFTWARE\App\AppX70162486c7554f7f80f481985d67586d\Application'
            - '\SOFTWARE\App\AppX70162486c7554f7f80f481985d67586d\DefaultIcon'
            - '\SOFTWARE\App\AppX37cc7fdccd644b4f85f4b22d5a3f105a\Application'
            - '\SOFTWARE\App\AppX37cc7fdccd644b4f85f4b22d5a3f105a\DefaultIcon'
    selection2:
        TargetObject|startswith:
            - 'HKU\'
        TargetObject|contains:
            # HKCU\SOFTWARE\Classes\AppXc52346ec40fb4061ad96be0e6cb7d16a\
            - '_Classes\AppXc52346ec40fb4061ad96be0e6cb7d16a\'
            # HKCU\SOFTWARE\Classes\AppX3bbba44c6cae4d9695755183472171e2\
            - '_Classes\AppX3bbba44c6cae4d9695755183472171e2\'
            # HKCU\SOFTWARE\Classes\CLSID\{E3517E26-8E93-458D-A6DF-8030BC80528B}\
            - '_Classes\CLSID\{E3517E26-8E93-458D-A6DF-8030BC80528B}\'
            - '_Classes\CLSID\{E08A0F4B-1F65-4D4D-9A09-BD4625B9C5A1}\Model'
```

Prevalence of basic tokens

- Has at least 1 token if:
  - No regular expression characters and can be tokenized
  - If it has at least 3 tokens between 2 regular expression characters

```
title: Octopus Scanner Malware
id: 805c55d9-31e6-4846-9878-c34c75054fe9
status: experimental
description: Detects Octopus Scanner Malware.
references:
  - https://securitylab.github.com/research/octopus-scanner-malware-open-source-supply-chain
tags:
  - attack.t1195
  - attack.t1195.001
author: NVISO
date: 2020/06/09
logsource:
  product: windows
  category: file_event
detection:
  selection:
    TargetFilename|endswith:
      - '\AppData\Local\Microsoft\Cache134.dat'
      - '\AppData\Local\Microsoft\ExplorerSync.db'
  condition: selection
falsepositives:
  - Unknown
level: high
```

```
logsource:
    category: registry_event
    product: windows
detection:
    selection:
        TargetObject:
            - 'HKCR\CLSID\{E08A0F4B-1F65-4D4D-9A09-BD4625B9C5A1}\Model'
        TargetObject|endswith:
              # covers HKU\* and HKLM..
            - '\SOFTWARE\App\AppXbf13d4ea2945444d8b13e2121cb6b663\Application'
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            - '_Classes\CLSID\{E08A0F4B-1F65-4D4D-9A09-BD4625B9C5A1}\Model'
```

Prevalence of basic tokens

- Has at least 1 token if:
  - No regular expression characters and can be tokenized
  - If it has at least 3 tokens between 2 regular expression characters
- **~70%** of all the Sigma open-source rules have at least 1 full token

```yaml
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status: experimental
description: Detects Octopus Scanner Malware.
references:
  - https://securitylab.github.com/research/octopus-scanner-malware-open-source-supply-chain
tags:
  - attack.t1195
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author: NVISO
date: 2020/06/09
logsource:
  product: windows
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  selection:
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            - '\SOFTWARE\App\AppXbf13d4ea2945444d8b13e2121cb6b663\DefaultIcon'
            - '\SOFTWARE\App\AppX70162486c7554f7f80f481985d67586d\Application'
            - '\SOFTWARE\App\AppX70162486c7554f7f80f481985d67586d\DefaultIcon'
            - '\SOFTWARE\App\AppX37cc7fdccd644b4f85f4b22d5a3f105a\Application'
            - '\SOFTWARE\App\AppX37cc7fdccd644b4f85f4b22d5a3f105a\DefaultIcon'
    selection2:
        TargetObject|startswith:
            - 'HKU\'
        TargetObject|contains:
            # HKCU\SOFTWARE\Classes\AppXc52346ec40fb4061ad96be0e6cb7d16a\
            - '_Classes\AppXc52346ec40fb4061ad96be0e6cb7d16a\'
            # HKCU\SOFTWARE\Classes\AppX3bbba44c6cae4d9695755183472171e2\
            - '_Classes\AppX3bbba44c6cae4d9695755183472171e2\'
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            - '_Classes\CLSID\{E3517E26-8E93-458D-A6DF-8030BC80528B}\'
            - '_Classes\CLSID\{E08A0F4B-1F65-4D4D-9A09-BD4625B9C5A1}\Model'
```

RQ2: Invariant Analysis In The Wild

Action type	File name	File path	...	sample Hash	Exec.id	Mach.id
File Create	setup.exe	CSIDL_PROFILE	...	AAA	1	abc
...	...	...	...	AAA	...	...

Action type	File name	File path	...	sample Hash	Exec.id	Mach.id
Mtx. Create	mtx!asjkf	-	...	ABC	5243523	abd
...	...	...	...	ABC	...	...

Extract parameter values

CSIDL_PROFILE
icon.png.wnry
setup.exe
cmd.exe|del|virus.exe

mtx!asjkf
CSIDL_PROFILE/folder1
runprogram.exe
icon.png
CSIDL_APPDATA/bin
config.ini
setup.exe

Split them by delimiter

CSIDL_PROFILE
icon
png
wnry
setup
exe
cmd
del
virus

mtx!asjkf
CSIDL_PROFILE
folder1
runprogram
exe
icon
png
CSIDL_APPDATA
bin
config
ini
setup
exe

RQ2: Invariant Analysis In The Wild

CSIDL_PROFILE
icon
png
wnry
setup
exe
cmd
del
virus

mtx!asjkf
CSIDL_PROFILE
folder1
runprogram
exe
icon
png
CSIDL_APPDATA
bin
config
ini
setup
exe

(Remove values that appear in benign samples)

RQ2: Invariant Analysis In The Wild

CSIDL_PROFILE
icon
png
wnry
setup
exe
cmd
del
virus

mtx!asjkf
CSIDL_PROFILE
folder1
runprogram
exe
icon
png
CSIDL_APPDATA
bin
config
ini
setup
exe

(Remove values that appear in benign samples)

wnry
virus

RQ2: Invariant Analysis In The Wild

CSIDL_PROFILE
icon
png
wnry
setup
exe
cmd
del
virus

mtx!asjkf
CSIDL_PROFILE
folder1
runprogram
exe
icon
png
CSIDL_APPDATA
bin
config
ini
setup
exe

(Remove values that appear in benign samples)

wnry → appears in 30/50 machines → **60%**
virus → appears in 10/50 machines → **20%**

RQ2: Invariant Analysis In The Wild

CSIDL_PROFILE
icon
png
wnry
setup
exe
cmd
del
virus

mtx!asjkf
CSIDL_PROFILE
folder1
runprogram
exe
icon
png
CSIDL_APPDATA
bin
config
ini
setup
exe

(Remove values that appear in benign samples and only 1 machine)

wnry → appears in 30/50 machines → **60%**
virus → appears in 10/50 machines → **20%**

Combination → ***(wnry|virus|…)***

appear in **65%** of the machines

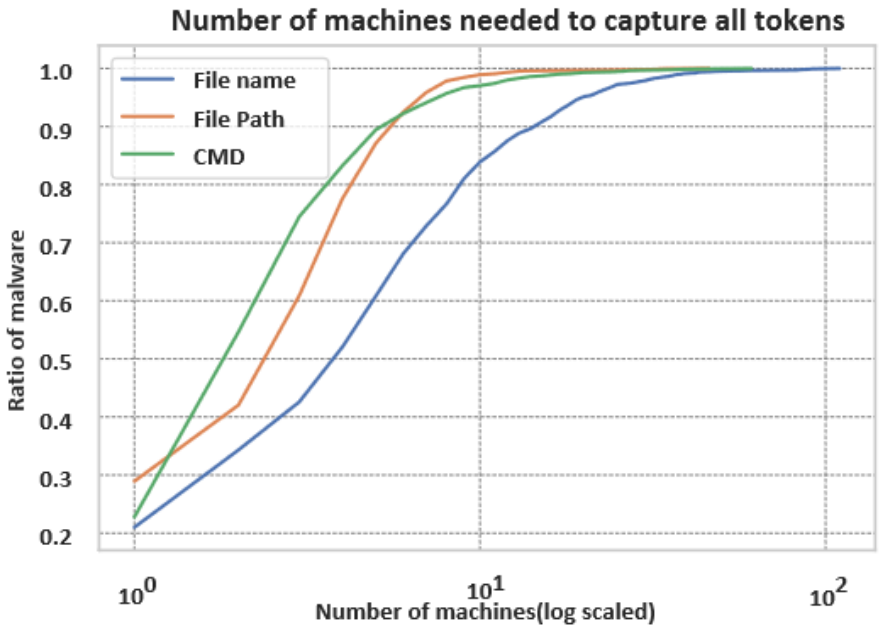
RQ2: How to capture all malware tokens?

RQ2: How to capture all malware tokens?

- Methodology:
  - We perform random sampling of **n** machines
  - Measure the amount of malware tokens
  - Compare with all the sample's malware tokens on all machines

RQ2: How to capture all malware tokens?

- Results:
  - File names are most difficult to completely capture.
  - CMD tokens and subdirectories captured with 10 machines.



RQ2: Invariant Analysis In The Wild

- How do these tokens detect?
- How to maximize coverage/detection?
  - **Assumption:** Sandbox is undetectable.

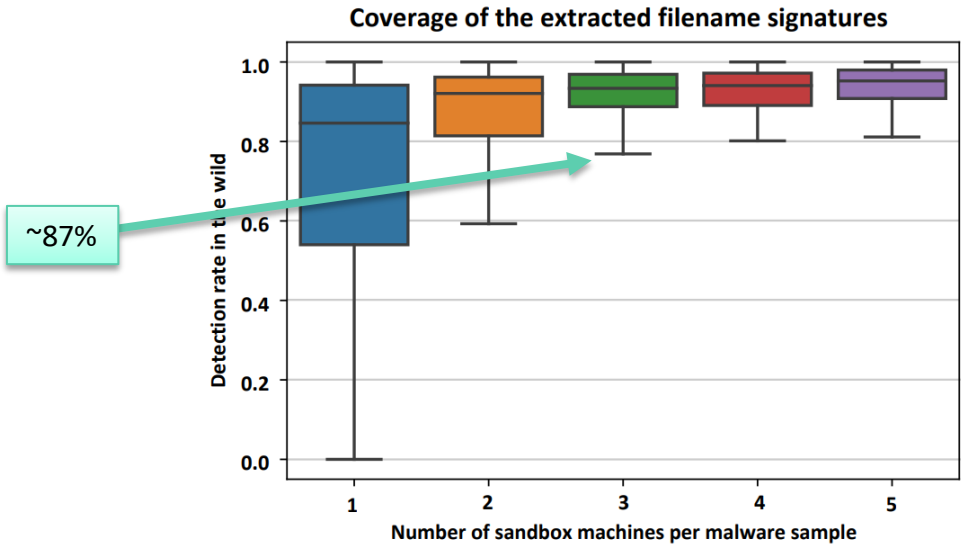
RQ2: Invariant Analysis In The Wild

- How do these tokens detect?
- How to maximize coverage/detection?
  - **Assumption:** Sandbox is undetectable, just like real machines.

- Pick **n** machines to get the bag of tokens
  - Check how much coverage would we get on the other machines.

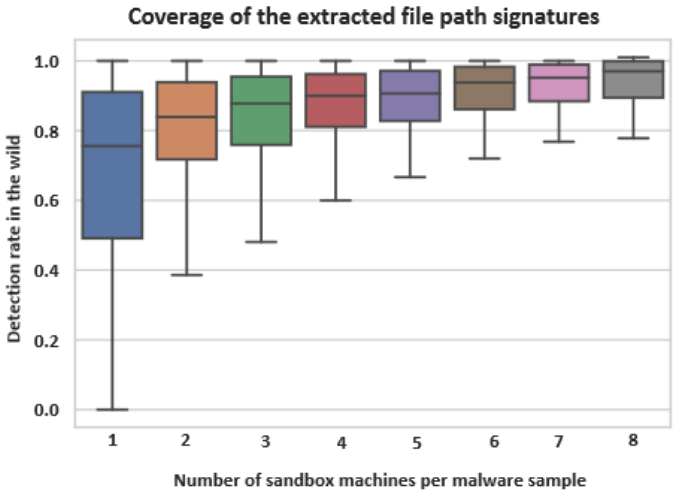
RQ2: Invariant Analysis In The Wild

- Maximum coverage in 3 randomly generated machines
  - For file name tokens
- One file name token doesn't appear in all machines.
  - Use more than 1 file name

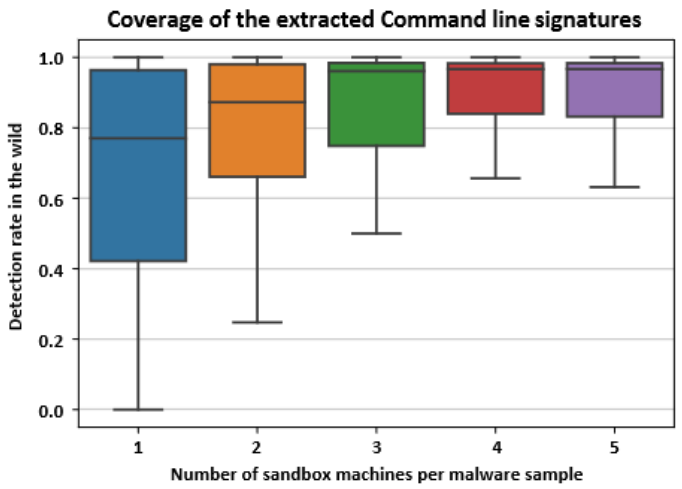


RQ2: Invariant Analysis In The Wild

- Analyst needs
  - 4 different sandboxes for CMD line
  - 7 for file path tokens
- Easier to obtain:
  - Poorer coverage than file name



(b)



(c)

How to create random sandboxes?

How to create random sandboxes?

- Use a random vm generator like SecGen [1]

[1] Schreuders, Z. Cliffe, et al. "Security Scenario Generator (SecGen): A Framework for Generating Randomly Vulnerable Rich-scenario VMs for Learning Computer Security and Hosting {CTF} Events." *ASE*. 2017.

How to create random sandboxes?

- Use a random vm generator like SecGen [1]
  - with the features proposed by Miramirkhani et al. [2]

TABLE I: Complete list of wear-and-tear artifacts.

Category	Name	Description	User	Sandbox	Baseline
System	totalProcesses	# of processes	94.4	35	41
	winupdt	# installed Windows updates	794	19	2
	sysevt	# system of system events	27K	8K	334
	appevt	# of application events	18K	2.4K	184
	syssrc	# sources of system events	78	49	48
	appsrc	# sources of application events	40	26	23
	sysdiffdays	Elapsed time since the first system event (days)	370	1.7K	0
	appdiffdays	Elapsed time since the first application event (days)	298	943	0
Disk	recycleBinSize	Total size of the recycle bin (bytes)	2.5G	50M	0
	recycleBinCount	# files in the recycle bin	109	3	0
	tempFilesSize	Total size of temporary system files (bytes)	302	24	8.2
	tempFilesCount	# temporary system files	411	60	10
	miniDumpSize	Total size of process crash minidump files (bytes)	3M	409K	0
	miniDumpCount	# of process crash minidump files	9	4	0
	thumbsFolderSize	Total size of the system's thumbnails folder (bytes)	63M	8M	2.6M
	desktopFileCount	# files on the desktop	34	6	3
Network	ARPCacheEntries	# entries in the ARP cache	19	4.5	5
	dnscacheEntries	# entries in the DNS resolver cache	151	4	3
	certUtilEntries	# URLs of previously downloaded CRLs	1.7K	210	6
	wirelessnetCount	# of cached wireless SSIDs	8	0	0
	tcpConnections	# of active TCP connections	77	27	16
	regSize	Size of the registry (in bytes)	144.8M	53M	35M

[1] Schreuders, Z. Cliffe, et al. "Security Scenario Generator (SecGen): A Framework for Generating Randomly Vulnerable Rich-scenario VMs for Learning Computer Security and Hosting {CTF} Events." *ASE*. 2017.
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How to create random sandboxes?

- Use a random vm generator like SecGen [1]
  - with the features proposed by Miramirkhani et al. [2]
- AV vendors can collect such features

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RQ3: Impact of Variability

- In terms of:
  - Clustering
  - Anomaly detection (AccessMiner[1] , SIEM systems etc)

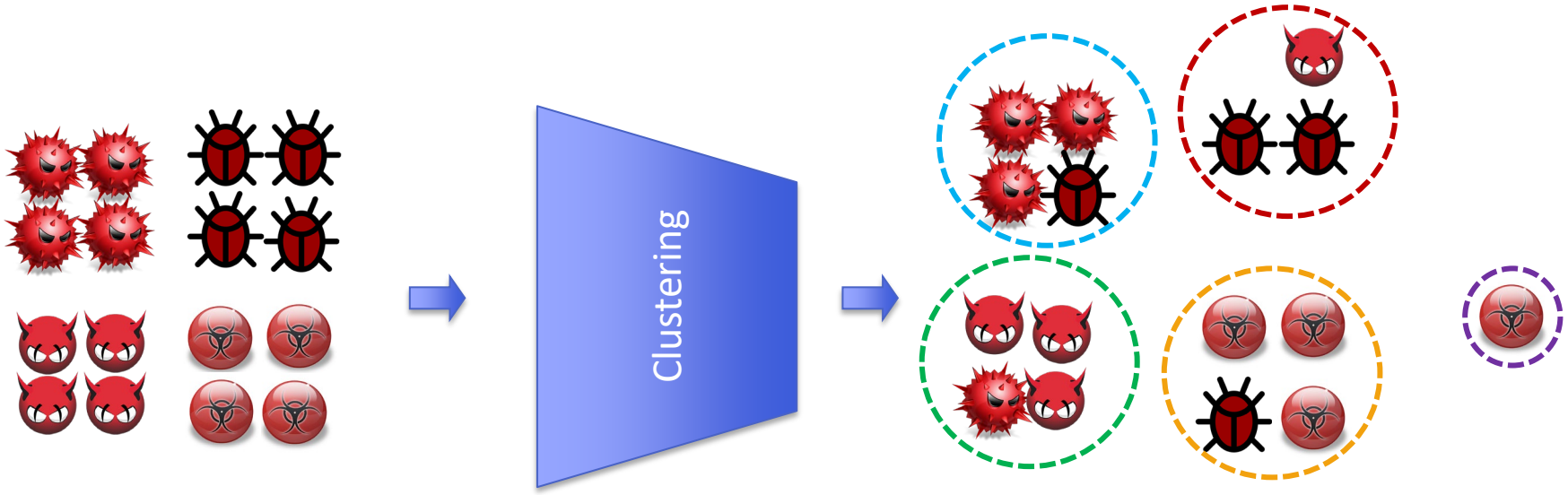
[1] Lanzi, et al. "Accessminer: using system-centric models for malware protection." *CCS* 2010.

RQ3: Impact of Variability (clustering)

- Questions:
  - How does malware behavior variability affect clustering?

RQ3: Impact Of Variability (clustering)

- Methodology:
  - Get 4 executions per malware sample in the same week
  - Reproduce the clustering by Bailey et al.[1]



[1] Bailey et al., Automated Classification and Analysis of Internet Malware, RAID 2007

RQ3: Impact of Variability (clustering)

- Results (out of **2424** malware samples):
  - 1,624 (67%) in the same cluster
  - 655 (27%) in 2 clusters
  - 121 (5%) in 3 clusters
  - 24 (1%) in 4 different cluster

RQ3: Impact of variability (clustering)

- Results (out of **2424** malware samples):
  - 1,624 (67%) in the same cluster
  - 655 (27%) in 2 clusters
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clustering results with 1 trace per sample
may not correctly cluster malware into families

RQ3: Impact of Variability (Anomaly detector)

- Questions:

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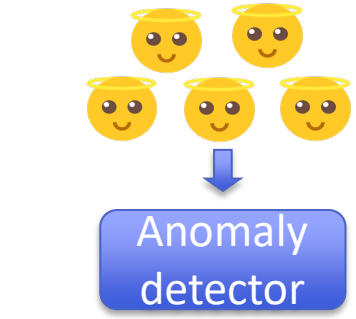
- Questions:
  - Is one execution per benign sample general enough?

RQ3: Impact of Variability (Anomaly detector)

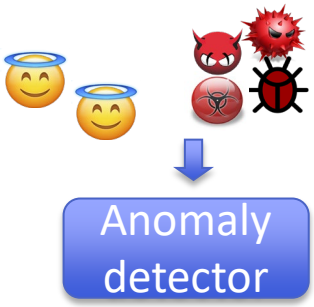
- Questions:
  - Is one execution per benign sample general enough?
  - What is the success rate for catching malware and PUP in the wild?

RQ3: Impact of Variability (Anomaly detector)

- Methodology:
  - Implement AccessMiner[1]
  - Select 90% of the benign samples and extract all file write directories
  - Test on all malware and remaining benign file write directories.



Extract features from some benign

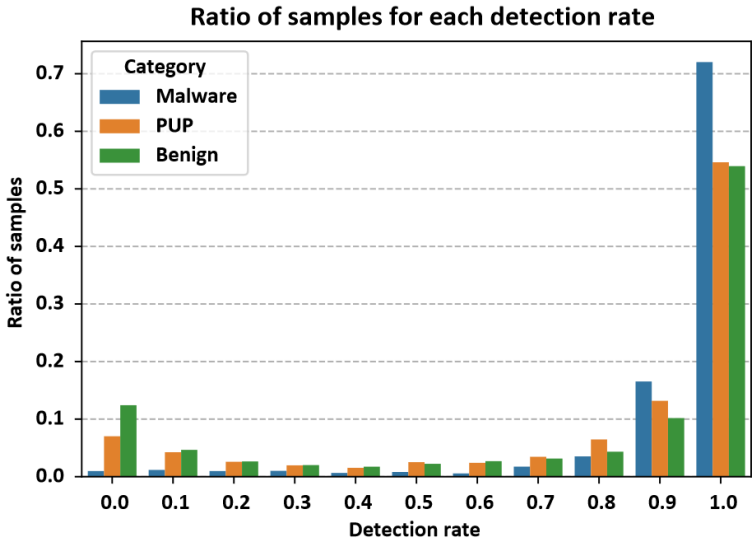


Classify other benign and malware

[1] Lanzi, et al. "Accessminer: using system-centric models for malware protection." *CCS* 2010.

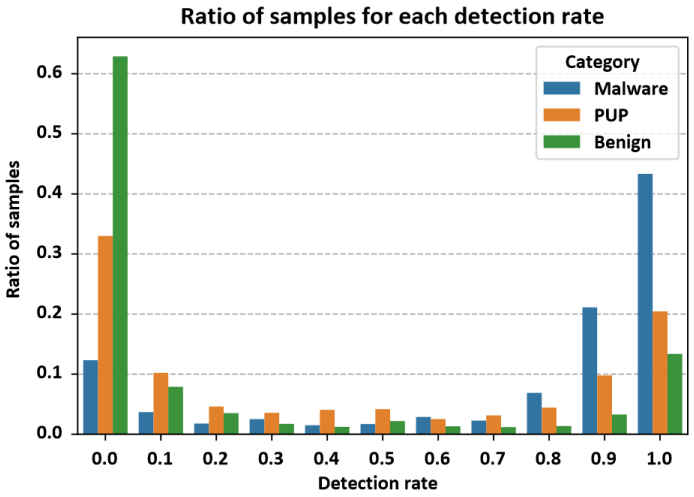
RQ3: Impact of Variability (Anomaly detector)

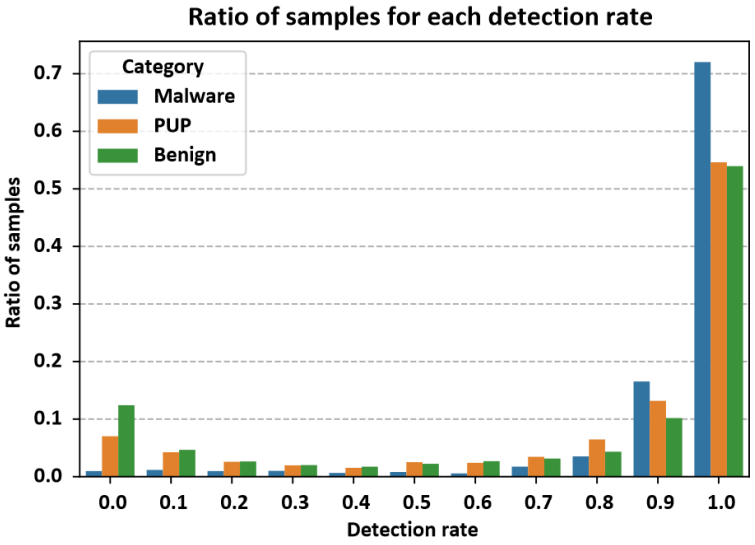
- Using 1 random benign execution for training
  - More malware can be detected in all machines.
  - High false-positive rate



RQ3: Impact of Variability (Anomaly detector)

- Using 1 random benign execution for training
  - More malware can be detected in all machines.
  - High false-positive rate
- Using all benign executions:
  - Significantly lower FP rate
  - Detection rate is low





RQ3: Summary

- When employing malware analysis methods:
  - Use multiple executions of the same malware samples
  - Use multiple executions of the benign samples

Conclusions

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- First measurement of malware behavior at scale:
  - Single trace per malware sample is not enough

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  - Across both time and machines

Conclusions

- First measurement of malware behavior at scale:
  - Single trace per malware sample is not enough
- Variability in malware is greater than PUP and benign
  - Across both time and machines
- It's still feasible to find invariant in malware behavior
  - AV vendors can safely do it

Thank you!

Erin Avllazagaj

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