A Semantics-based Approach to Malware Detection

Mila Dalla Preda – University of Verona, Italy
Mihai Christodorescu, Somesh Jha – University of Wisconsin, USA
Saumya Debray – University of Arizona, USA

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A Few Basic Definitions

Malware represents malicious software.

Malware detector is a program $D$ that determines whether another program $P$ is infected with a malware $M$.

$$D(P, M) = \begin{cases} 
\text{True} & \text{if } D \text{ determines that } P \text{ is infected with } M \\
\text{False} & \text{otherwise}
\end{cases}$$
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$$

An ideal malware detector detects all and only the programs infected with $M$, i.e., it is sound and complete.

- **Sound** = no false positives (no false alarms)
- **Complete** = no false negatives (no missed alarms)
There is more malware every year.
Malware Trends

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But the number of malware families has almost no variation.

Beagle family has 197 variants (as of Nov. 30).
Warezov family has 218 variants (as of Nov. 27).
The Malware Threat

Current detectors are signature-based:

\[ P \text{ matches byte-signature } sig \implies P \text{ is infected} \]

Signature-based detectors, when sound, are not complete.

Malware writers use obfuscation to evade current detectors.
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Virus–antivirus “coevolution”
  1. Malware writers create new, undetected malware.
  2. Antimalware tools are updated to catch the new malware.
  3. Repeat...
Common Obfuscations

- Nop insertion
- Register renaming
- Junk insertion
- Code reordering
- Encryption
- Reordering of independent statements
- Reversing of branch conditions
- Equivalent instruction substitution
- Opaque predicate insertion
- ... and many others...
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Obfuscation Example

(Pseudo-)Code:

```plaintext
mov eax, [edx+0Ch]
push ebx
push [eax]
call ReleaseLock
```
### Obfuscation Example

<table>
<thead>
<tr>
<th>(Pseudo-)Code:</th>
<th>Obfuscated code (junk):</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>mov eax, [edx+0Ch]</code></td>
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<tr>
<td><code>push ebx</code></td>
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<tr>
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<tr>
<td><code>call ReleaseLock</code></td>
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(Pseudo-)Code:

mov eax, [edx+0Ch]
push ebx
push [eax]
call ReleaseLock

Obfuscated code (junk + reordering):

mov eax, [edx+0Ch]
jmp +3
push ebx
dec eax
jmp +4
inc eax
jmp -3
call ReleaseLock
jmp +2
push [eax]
jmp -2
Recent developments based on deep static analysis:

- Detecting Malicious Code by Model Checking [Kinder et al. 2005]
- Semantics-Aware Malware Detection [Christodorescu et al. 2005]
- Behavior-based Spyware Detection [Kirda et al. 2006]
Recent developments based on deep static analysis:

1. Detecting Malicious Code by Model Checking [Kinder et al. 2005]
2. Semantics-Aware Malware Detection [Christodorescu et al. 2005]

Lack of a formal framework for assessing these techniques.
Our Contributions

Challenges:

- Many different obfuscations
- Obfuscations are usually combined
- Detection schemes usually rely on static/dynamic analyses
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A framework for assessing the resilience to obfuscation of malware detectors.

- Obfuscation as transformation of trace semantics
- Malware detection as abstract interpretation of trace semantics
- Composing obfuscations vs. composing detectors
Two Worlds of Malware Detectors

Malware detector on finite semantic structure

- Disassembler
- CFG construction
- Other analyses
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Malware detector on trace semantics
Abstract Interpretation

Design approximate semantics of programs [Cousot & Cousot ’77, ’79].

Galois Connection: $\langle C, \alpha, \gamma, A \rangle$, $A$ and $C$ are complete lattices.

$\langle \text{Abs}(C), \sqsubseteq \rangle$ set of all possible abstract domains, $A_1 \sqsubseteq A_2$ if $A_1$ is more concrete than $A_2$
Outline

- Semantic Malware Detector
- Soundness and Completeness
- Classifying Obfuscations
- Composing Obfuscations
- Proving Soundness and Completeness
A program $P$ is infected by malware $M$, denoted $M \hookrightarrow P$ if (a part) of $P$ execution is similar to that of $M$:
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$$S[M] \subseteq S[P]$$
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$$\exists \text{ restriction } r : S[M] \subseteq \alpha_r(S[P])$$

program trace

malware trace
A program $P$ is infected by malware $M$, denoted $M \rightarrow P$ if (a part) of $P$ execution is similar to that of $M$:

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Vanilla Malware i.e. not obfuscated malware
Obfuscated Malware

\[ \mathcal{O} : \mathbb{P} \rightarrow \mathbb{P} \text{ obfuscating transformation} \]

\[ \alpha : \text{Sem} \rightarrow \text{Abstraction} \text{ that discards the details changed by the obfuscation while preserving maliciousness} \]

\[ \exists \text{ restriction } r : \alpha (S[M]) \subseteq \alpha (\alpha_r (S[P])) \]
\( \mathcal{O} : \mathcal{P} \rightarrow \mathcal{P} \) obfuscating transformation

\( \alpha : \text{Sem} \rightarrow \text{A abstraction} \) that discards the details changed by the obfuscation while preserving maliciousness

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Precision of the Semantic Malware Detector (SMD) depends on $\alpha$.
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A SMD on $\alpha$ is **complete** w.r.t. a set $\mathcal{O}$ of transformations if $\forall \mathcal{O} \in \mathcal{O}$:

$$\mathcal{O}(M) \rightarrow P \Rightarrow \begin{cases} \exists \text{ restriction } r : \\
\alpha(S[M]) \subseteq \alpha(\alpha_r(S[P])) \end{cases}$$

always detects programs that are infected (no false negatives)
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\end{cases}$$

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If $\alpha$ is **preserved** by $\mathcal{O}$ then the SMD on $\alpha$ is **complete** w.r.t. $\mathcal{O}$. 
Sound vs. Complete

Precision of the Semantic Malware Detector (SMD) depends on $\alpha$.

A SMD on $\alpha$ is sound w.r.t. a set $\mathcal{O}$ of transformations if:

$$\exists \text{ restriction } r : \alpha(S[M]) \subseteq \alpha(\alpha_r(S[P])) \implies \exists \mathcal{O} \in \mathcal{O} : \mathcal{O}(M) \hookrightarrow P$$

never erroneously claims a program is infected (no false positives)
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Classifying Obfuscations

\[ O : \mathbb{P} \rightarrow \mathbb{P} \text{ is a conservative obfuscation if} \]
\[ \forall \text{trace}_1 \in S[\mathbb{P}], \exists \text{trace}_2 \in S[O[\mathbb{P}]]: \text{trace}_1 \text{ is sub-sequence of trace}_2 \]
Conservative Obfuscations

Abstraction $\alpha_c$ handles conservative obfuscations:

$$\alpha_c[X](Y) = X \cap \text{SubSequences}(Y)$$

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The SMD on $\alpha_c$ is sound and complete w.r.t. conservative obfuscations.

Abstraction $\alpha_c$ returns the set of malware traces that are subsequences of some program trace.
Classifying Common Obfuscations

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Obfuscated code (junk + reordering):

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mov eax, [edx+0Ch]
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call ReleaseLock
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```
Conservative Obfuscation Example

(Pseudo-)Code:

Obfuscated code (junk + reordering):

1
2
3
4

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3
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Non-Conservative

Approach 1: Find a canonical transformation
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(Pseudo-)Code:

mov eax, [edx+0Ch]
push ebx
push [eax]
call ReleaseLock

Obfuscated Code (Renaming):

mov edi, [eax+0Ch]
push ecx
push [edi]
call ReleaseLock
Non-Conservative

Approach 1: Find a canonical transformation

(Pseudo-)Code:

```
mov R1, [R2+0Ch]
push R3
push [R1]
call ReleaseLock
```

Obfuscated Code (Renaming):

```
mov R1, [R2+0Ch]
push R3
push [R1]
call ReleaseLock
```
Non-Conservative

Program infection: $M \leftrightarrow P$ if $\exists$ restriction $r : S[M] \subseteq \alpha_r(S[P])$
Program infection: \( M \hookrightarrow P \) if \( \exists \) restriction \( r : S[M] \subseteq \alpha_r(S[P]) \)

Approach 2: Further abstractions

Interesting Malware States: \( I \subseteq \text{States}[M] \):

\[
M \hookrightarrow P \text{ if } \exists r : \alpha_I(S[M]) \subseteq \alpha_I(\alpha_r(S[P]))
\]
Non-Conservative

Program infection: $M \rightarrow P$ if $\exists$ restriction $r : S[M] \subseteq \alpha_r(S[P])$

Approach 2: Further abstractions

Interesting Malware States: $I \subseteq States[M]$: 

$M \rightarrow P$ if $\exists r : \alpha_I(S[M]) \subseteq \alpha_I(\alpha_r(S[P]))$

Interesting Malware Traces: $X \subseteq S[M]$

$M \rightarrow P$ if $\exists r : X \subseteq \alpha_r(S[P])$
Malware writers combine different obfuscations to avoid detection.

The property of being conservative is preserved by composition \( \Rightarrow \) abstraction \( \alpha_c \).

Under certain assumptions we can handle the composition of non-conservative obfuscations.
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Identifying the class of obfuscators to which a malware detector is resilient can be a complex and error-prone task.

Obfuscators and detectors can be expressed on executions traces.

A detector is resilient to an obfuscator if it can “abstract away” the obfuscator’s effect on the program.

Case study: Semantics-Aware Malware Detection Algorithm proposed by [Christodorescu et al. 2005].

- Complete for code reordering
- Complete for junk insertion
- Complete for variable renaming
Conclusions

Malware detection as abstraction of program semantics vs. Obfuscation as transformation of program semantics

We can now determine:
- Whether a detector is resilient to a set of obfuscations
- How complex a detector has to be to handle a given obfuscation

Open Problems:
- Can we handle some interesting classes of non-conservative obfuscations?
- How does one design a semantic detector based on trace semantics?
- Connecting cryptographic and program analysis views of obfuscation
Thank you!