New approaches for chasing metamorphic malware

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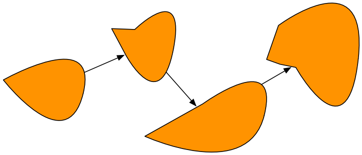
Metamorphic malware

The malware applies semantics-preserving transformations (e.g. obfuscations) to mutate its own code as it propagates.



ATTACKING METAMORPHISM

Our research directions

Metamorphism is mainly based on obfuscation techniques:

- We can study obfuscation techniques
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- We can study obfuscation techniques
  - Different from reverse engineering: we are not interested in the original code, we look for properties characterizing semantic invariants;
- We can extract behavioural malware characterizations
  - We can use higher-order (abstract) non-interference properties for characterizing the interaction of malware with the environment;
  - Further application: We can study how to defeat anti-emulation techniques.

EXAMPLE

(Pseudo-)Code:

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mov eax, [edx+0Ch]
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```
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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
```

PROTECTION BY OBSCURITY

$\mathfrak{O} : \mathbb{P} \rightarrow \mathbb{P}$ is a code obfuscator if it is an obfuscating compiler:

- It is potent: $\mathfrak{O}(P)$ is *more complex* (ideally unintelligible) than P;
- It preserves the observational behaviour of programs $[\![\mathfrak{O}(P)]\!] = [\![P]\!]$ [C. Collberg et al. '97, '98]

The limit. Obfuscating programs is (im)possible:

Even under restrictive hypothesis a general purpose obfuscator generating perfectly unintelligible code (virtual black-box) does not exist! [Barak et al. '01]

The challenge. Design obfuscators that work against specific attacks

Extensional properties of programs are undecidable [Rice '53]
....so formal methods and static analysis are born!

APPROXIMATION VS OBSCURITY

- Because of undecidability we need approximation
- Even if decidable, it is typically too complex to trace/analyze/understand (500kC $\sim$ 600 mY) so we need approximation
- Approximation is pervasive in computing and code understanding

There are only approximated interpretations of programs

- Making obscure is making the approximated interpreter blind!
- Potent obscure transformations correspond to hardly improvable approximations

How can we formalize all this?

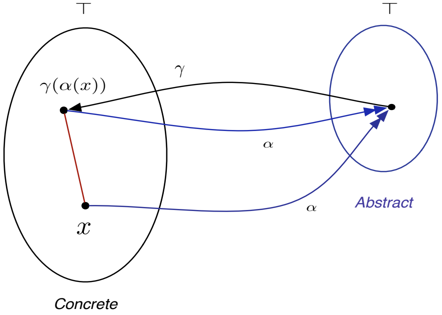
WHY ABSTRACT INTERPRETATION?

Abstract Interpretation (1977) is the a general model for the (static or dynamic) approximation of semantics of discrete dynamic systems

- Including: Static program analysis, dynamic analysis, profiling, debugging, tracing, compilation, de-compilation, type checking and type inference, model checking and predicate abstraction, trajectory evaluation, testing, proof systems, etc.

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.

Closures: $\langle uco(C), \sqsubseteq \rangle$ set of all possible abstract domains,

$A_1 \sqsubseteq A_2$ if A_1 is more concrete than A_2

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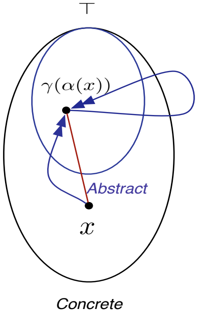

$\gamma \circ \alpha \in uco(C)$

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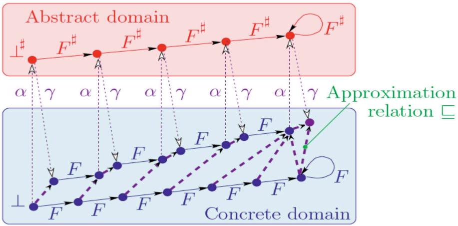
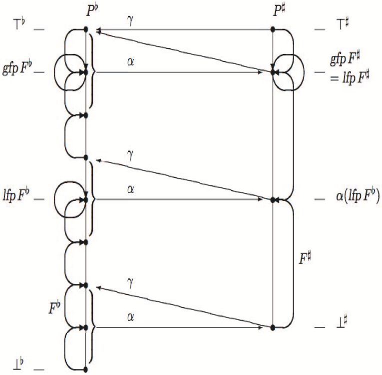
APPROXIMATING INTERPRETATION: BCA





G is a sound approximation of F if

$$\alpha \circ F \circ \gamma \sqsubseteq G$$

SOUNDNESS AND COMPLETENESS

[Cousot & Cousot '79]

- A program $P \in \mathbb{P}$ and a domain of computation C
- An interpreter: $[\![\cdot]\!] : \mathbb{P} \times C \longrightarrow C$
- (Approximate) observable properties: $\rho = \gamma \circ \alpha \in uco(C)$
- DERIVE A SOUND APPROXIMATE SPECIFICATION $[\![P]\!]^\sharp$

$$\rho([\![P]\!](x)) \leq [\![P]\!]^\sharp(x)$$

- THE LIMIT CASE: COMPLETENESS

$$\rho([\![P]\!](x)) = [\![P]\!]^\sharp(x) \text{ iff } \rho([\![P]\!](x)) = \rho([\![P]\!](\rho(x)))$$

SOUNDNESS AND COMPLETENESS

- `WhichChess` : $Img \longrightarrow \wp(Chess)$ returns the type of chess on the chessboard.
- $\rho : Img \longrightarrow Img$ such that: ρ () = 
- $\eta : \wp(Chess) \longrightarrow [0, 12]$ counts the number of different types of chess

η (`WhichChess` (ρ ())) = η (`WhichChess` ())

$= 12$

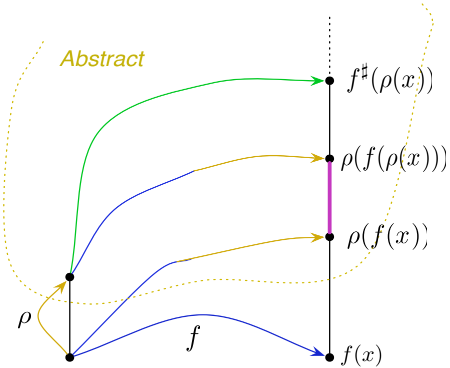
$\geq$ η (`WhichChess` ())

$= 7$

COMPLETENESS IN ABSTRACT INTERPRETATION

- BACKWARD SOUNDNESS:
  NO INFORMATION IS LOST BY APPROXIMATING THE INPUT/OUTPUT

- $\rho \circ f \leq \rho \circ f \circ \rho$



COMPLETENESS IN ABSTRACT INTERPRETATION

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  NO LOSS OF PRECISION IS ACCUMULATED BY APPROXIMATING THE INPUT
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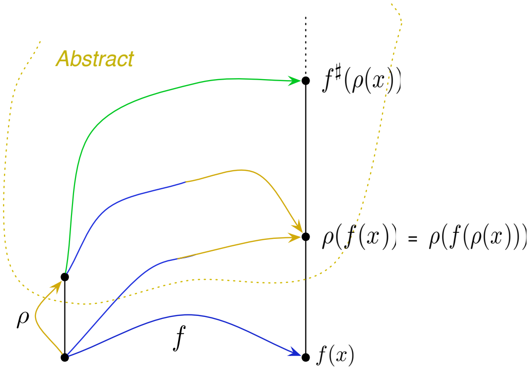

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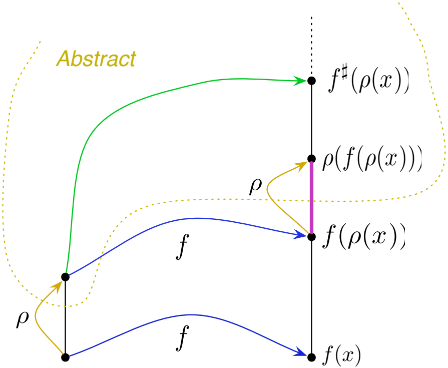

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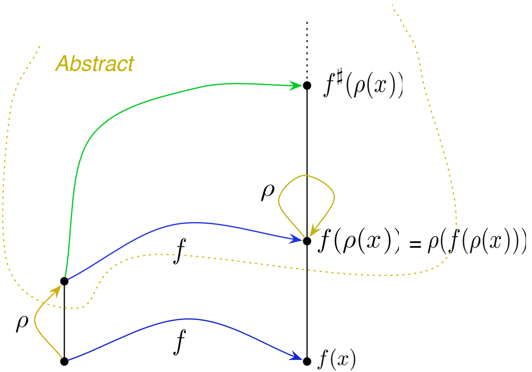

OBSCURITY AS INCOMPLETENESS

Failing precision means failing completeness!

Obfuscating programs is making abstract interpreters incomplete

- Let $\rho \in uco(\Sigma)$ with Σ semantic objects (data, traces etc)
- A program transformation $\tau : \mathbb{P} \to \mathbb{P}$ such that $[\![P]\!] = [\![\tau(P)]\!]$.
- ρ $\mathcal{B}$-complete for $[\![\cdot]\!]$ if $\rho([\![P]\!]) = [\![P]\!]^\rho$

τ obfuscates P if $[\![P]\!]^\rho \sqsubset [\![\tau(P)]\!]^\rho$

$$[\![P]\!]^\rho \sqsubset [\![\tau(P)]\!]^\rho \iff \rho([\![\tau(P)]\!]) \sqsubset [\![\tau(P)]\!]^\rho$$

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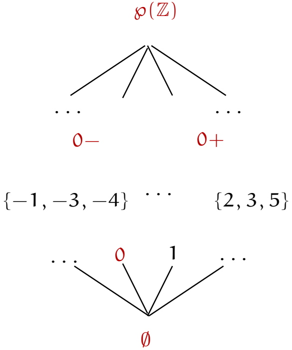
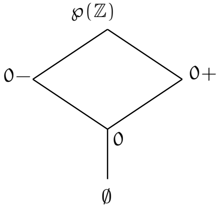
$P : \mathtt{x} = \mathtt{a} * \mathtt{b}$

$Sign$ is an obvious abstraction of $\wp(\mathbb{Z})$:





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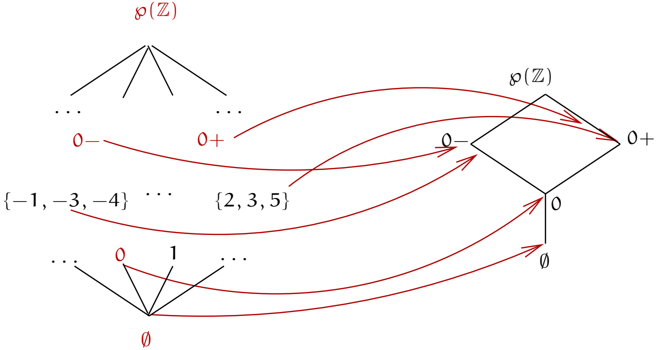

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$$P: \quad \mathtt{x = a * b} \quad \longrightarrow \quad \tau(P): \quad \begin{array}{l} \mathtt{x} = 0; \\ \mathtt{if}\ \mathtt{b} \leq 0\ \mathtt{then}\ \{\mathtt{a} = -\mathtt{a}; \mathtt{b} = -\mathtt{b}\}; \\ \mathtt{while}\ \mathtt{b} \neq 0\ \{\mathtt{x} = \mathtt{a} + \mathtt{x}; \mathtt{b} = \mathtt{b} - 1\} \end{array}$$

- $Sign$ is complete for P:
  - ✔ $[\![P]\!]^{Sign} = \lambda \mathsf{a}, \mathsf{b}.\ Sign(\mathsf{a} * \mathsf{b})$
- $Sign$ is incomplete for $\tau(P)$:
  - ✔ $[\![\tau(P)]\!]^{Sign} = \lambda \mathsf{a}, \mathsf{b}. \begin{cases} 0 & \text{if } \mathsf{a} = 0 \vee \mathsf{b} = 0 \\ \wp(\mathbb{Z}) & \text{otherwise} \end{cases}$
- Is there any way to get $\tau(P)$ systematically out of P?

EXPLOITING INCOMPLETENESS

Maximize $[\![P]\!]^\rho$ incompleteness!

- The abstraction is the specification of the attacker
  - ✔ Profiling: Abstract memory keeping only (partial) resource usage
  - ✔ Tracing: Abstraction of traces (e.g., by trace compression)
  - ✔ Slicing: Abstraction of traces (relative to variables)
  - ✔ Monitoring: Abstraction of trace semantics ([Cousot&Cousot POPL02])
  - ✔ Decompilation: Abstracts syntactic structures (e.g., reducible loops)
  - ✔ Disassembly: Abstracts binary structures (e.g., recursive traversal)
- Each abstraction is incomplete for a concrete enough trace semantics
- Maximize incompleteness by code transformation: Obfuscation
- Exploit incompleteness for hiding information: Steganography

THE IDEA [GIACOBAZZI, JONES & MASTROENI '12]

Build a *general-purpose program transformer* by programming a self-interpreter in a style to give the desired transformation

CLAIM: $[\![\mathtt{P}]\!] = [\![\mathtt{P}']\!]$, by simple equational reasoning:

$[\![\mathtt{P}]\!](\mathtt{d})$	$=$	$[\![\mathtt{interp}]\!](\mathtt{P},\mathtt{d})$	definition of self-interpreter
	$=$	$[\![[\![\mathtt{spec}]\!](\mathtt{interp},\mathtt{P})]\!](\mathtt{d})$	definition of specializer
	$=$	$[\![\mathtt{P'}]\!](\mathtt{d})$	definition of P'

Therefore the function

$$\mathtt{P} \longmapsto [\![\mathtt{spec}]\!](\mathtt{interp},\mathtt{P})$$

is a *semantics-preserving program transformer*!!

We need to *change the interpretation*: $\mathtt{interp} \rightsquigarrow \mathtt{interp}^{+}$

An easy example: Data obfuscation

Similar to Drape 2004 technique, but automated!!

Modify the simple self-interpreter so that

- all values in the store are obfuscated, e.g., by multiplying by 2: mutual inverse functions $obf(x)$ and $dob(x)$ obfuscate or invert obfuscation.
- We consistently modify `interp` so that:
  - ✔ input values are obfuscated in the initial store;
  - ✔ variable values are obfuscated just before putting in the store;
  - ✔ output values are de-obfuscated in the program's final store;
  - ✔ expression evaluation yields non-obfuscated values:
    - » constant values are not obfuscated,
    - » variables' values must be de-obfuscated when got from the store

AN EASY EXAMPLE: THE INTERPRETER

input P, d; — Program to be interpreted, and *its* data

$pc := 2$; — Initialise program counter and obfuscated store:

$store := [in \mapsto obf(d), out \mapsto obf(0), x_1 \mapsto obf(0), \ldots]$;

while $pc < length(\mathtt{P})$ **do**

  $instruction := lookup(\mathtt{P}, pc)$;

  case $instruction$ **of** — Dispatch on syntax

  skip : $pc := pc + 1$; — Obfuscate values when stored:

  $x := e$: $store := store[x \mapsto obf(eval(e, store))]$; $pc := pc + 1$;

  $\ldots$ **endw** ;

output $dob(store[out])$;

$obf(V) = 2 * V$; $dob(V) = V/2$ — Obfuscation/de-obfuscation

$eval(e, store) =$ **case** e **of**

  $constant$: $obf(e)$

  $variable$: $dob(store(e))$ — De-obfuscate variable values

  $e1 + e2$: $eval(e1, store) + eval(e2, store)$

  $e1 - e2$: $eval(e1, store) - eval(e2, store)$

  $\ldots$

AN EASY EXAMPLE: THE OUTPUT

The source program is automatically transformed into this equivalent obfuscated one

1. **input** x;		1. **input** x;
		1.5. $x := 2 * x$; Obfuscate input x
2. $y := 2$;		2. $y := 2 * 2$; Obfuscate $y := 2$
3. **while** $x > 0$ **do**		3. **while** $x/2 > 0$ **do** De-obfuscate x
4. $y := y + 2$;	$\longmapsto$	4. $y := 2 * (y/2 + 2)$;
5. $x := x - 1$		5. $x := 2 * (x/2 - 1)$
endw		**endw**
6. **output** y;		6. **output** $y/2$; De-obfuscate output
7. **end**		7. **end**

SIGN ANALYSIS

- Sign analysis is complete for multiplication $*$: exact information.
- Sign analysis is incomplete for addition $+$: imprecise information

$*$	$-$	0	$+$
$-$	$+$	0	$-$
0	0	0	0
$+$	$-$	0	$+$

$+$	$-$	0	$+$
$-$	$-$	$-$	$\top(!)$
0	$-$	0	$+$
$+$	$\top(!)$	$+$	$+$

Our trick: ...let the interpreter evaluate!

$$
\begin{aligned}
eval(e, store) \; = \; & \textbf{case } e \textbf{ of} \\
& e1 + e2 \; : eval(e1, store) + eval(e2, store) \\
& e1 * e2 \; : \textbf{let } v1 = eval(e1, store), v2 = eval(e2, store) \\
& \qquad\qquad \textbf{in } \; v1 * (v2 - 1) + v1
\end{aligned}
$$

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P:

```
1. input x;
2. y := 2;
3. while x > 0 do
     4. y := y * y;
     5. x := x - 1
   endw
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```

$\longmapsto$

P':

```
1. input x;
2. y := 2;
3. while x > 0 do
     4. y := y * (y - 1) + y;
     5. x := x - 1
   endw
6. output y;
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Sign analysis yields $y \mapsto +$ in P, but it yields $y \mapsto \top$ in P'.

The big goal

- A deep relation between obfuscation and interpretation
- Attack and defense are two aspects of interpretation
- Define a uniform framework for information concealment in programming languages
  - ✔ General enough to include most known methods
  - ✔ Formal enough to provide a (possibly) provable secure environment for obfuscation (and steganography) relatively to a fixed attacker
  - ✔ Rich enough to provide advanced design and evaluation methods
  - ✔ Practical enough to generate truly obfuscated
- The goal: *develop a theory and practice for code obfuscation (and steganography) in order to make these technologies as practical as analogous ones in other media (e.g., in DRM of audio and video)*

Completeness and metamorphism

Obfuscation is incompleteness

Obfuscation deceives all analyses incomplete wrt the made transformation

Hence...

Incompleteness transformers characterise the set of deceived analyses! [Giacobazzi & Mastroeni '12]

Metamorphism is obfuscation

Malware protects its code by using obfuscation techniques.

Hence...

Completeness transformers characterises the set of successful malware detection analyses?

Malware detection

Malware detector

$$\mathcal{D}(P, M) = \begin{cases} \textit{true} & \text{if } \mathcal{D} \text{ determines that } P \text{ is infected with } M \\ \textit{false} & \text{otherwise} \end{cases}$$

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An ideal malware detector is sound and complete:

- SOUND = no false positives (no false alarms)

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- SOUND = no false positives (no false alarms)
- COMPLETE = no false negatives (no missed alarms)

CHASING METAMORPHISM

In order to detect metamorphic malware variants malware detector should be based on SEMANTIC program features.

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Formal framework for malware detection based on program semantics and abstract interpretation.

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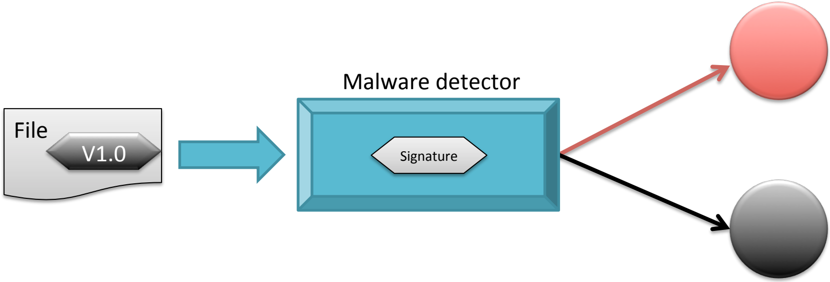
LIMIT

It assumes that the malware APPENDS its code and behaviour to the target program without interacting with it

HOANI AND MD: THE IDEA

Metamorphism *defeats* the malware detector if it does generate an INTERFERENCE!



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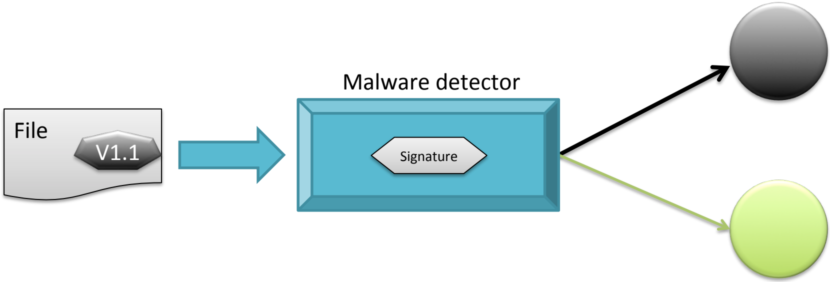

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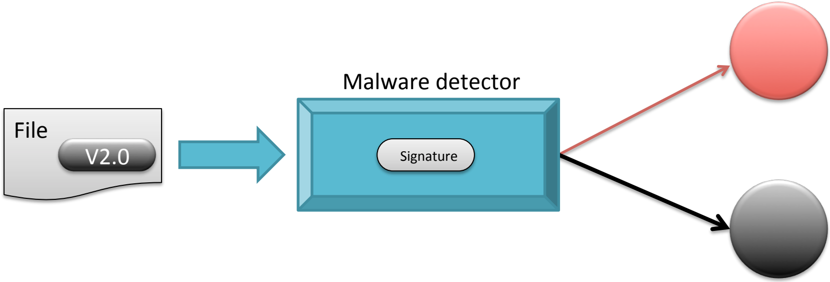

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Abstract non-interference (ANI) generalizes NI by weakening the dependences between data

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High Order ANI (HOANI): Lift the ANI framework to programs.

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- Consider a set $\mathbb{O}$ of obfuscating transformations ranged over by $\mathcal{O}$.
- Let $M \hookrightarrow P$ denote that program P is infected with malware M.

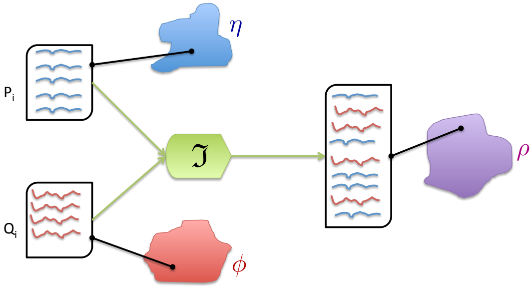
Relative soundness and completeness

$\mathcal{D}$ is SOUND for $\mathbb{O}$ if $\mathcal{D}(P, M) = \textit{true} \;\Rightarrow\; \exists \mathcal{O} \in \mathbb{O} : \mathcal{O}(M) \hookrightarrow P$

$\mathcal{D}$ is COMPLETE for $\mathbb{O}$ if $\forall \mathcal{O} \in \mathbb{O} : \mathcal{O}(M) \hookrightarrow P \;\Rightarrow\; \mathcal{D}(P, M) = \textit{true}$

HOANI

$$[\![P_1]\!]^\eta = [\![P_2]\!]^\eta \wedge [\![Q_1]\!]^\phi = [\![Q_2]\!]^\phi \Rightarrow [\![\mathfrak{I}(Q_1, P_1)]\!]^\rho = [\![\mathfrak{I}(Q_2, P_2)]\!]^\rho$$



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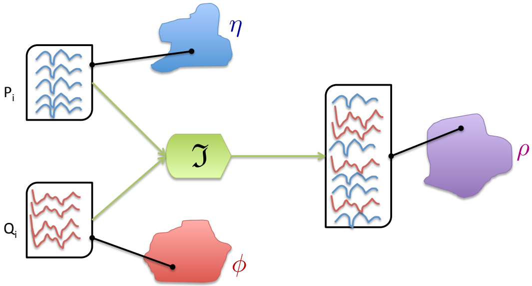

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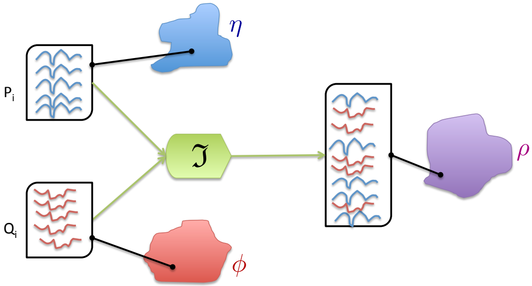

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Let ϕ the semantic property preserved by the ME:

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We can characterize the **most concrete** property ϕ such that *ANIMD* is SOUND and COMPLETE for $\mathbb{O}_\phi$!

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WHAT'S NEW IN *ANIMD*

$ANIMD_\rho(M, P)$ is more general than $SMD_\rho(M, P)$.

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    - Derive the observation property ρ that characterizes detection for $ANIMD_\rho$;
- This approach can be used for avoiding anti-emulation techniques used by modern malware [Dinaburg et al. '08, Kang et al. '09].