CUBISMO: Decloaking Server-side Malware via Cubist Program Analysis

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Cubist Art

"Cubist art analyzes **multiple aspects** of an object, **breaks them down**, and **reassembles** them for presentation."

Pablo Picasso, 1910
Girl with a Mandolin (Fanny Tellier)
oil on canvas, 100.3 x 73.6 cm
Museum of Modern Art, New York

Server-side (PHP) malware

```php
<?php
error_reporting(0);
@ini_set('error_log',NULL);
@ini_set('log_errors',0);
@ini_set('display_errors','Off');
@eval(base64_decode('
aWYobWQ1KCRfUE9TVFsicGYiXSkgPT09I
CIuLi...DQ4YzJOeWFYQi4uLkwySnZaSG
srUEM5b2RHMXNQZzBLIikpOw=='));
@ini_restore('error_log');
@ini_restore('display_errors');
...
```

(a) Normalized Program

```php
<?php
error_reporting(0);
@ini_set('error_log',NULL);
@ini_set('log_errors',0);
@ini_set('display_errors','Off');
if(md5($_POST["pf"]) === "...")
  eval(base64_decode($_POST["..."]));
...
if($patchedfv === "..." ) {
  @ob_end_clean();  die;
}
eval(base64_decode("JHVFUkN6ID0gJys9I
FpYUy4uLj...ka0N4dE9KT2prcigpOyA="));
@ini_restore('error_log');
@ini_restore('display_errors');
...
```

(b) Deobfuscated Program 1

```php
<?php
error_reporting(0);
@ini_set('error_log',NULL);
@ini_set('log_errors',0);
@ini_set('display_errors','Off');
if(md5($_POST["pf"]) === "...")
  eval(base64_decode($_POST["..."]));
...
if($patchedfv === "..." ) {
  @ob_end_clean();  die;
}
$uERCz = '+= ZXS...>68,Q;';
$kCxtOJOjkr = $uERCz('', '8ZfCK<:.>
==72-XE08...RA715e<Ei>Z5M83fSbQ:O');
$kCxtOJOjkr();
@ini_restore('error_log');
@ini_restore('display_errors');
...
```

(c) Deobfuscated Program 2

CUBISMO, 2019

PHP Malware and Its Multiple Aspects,

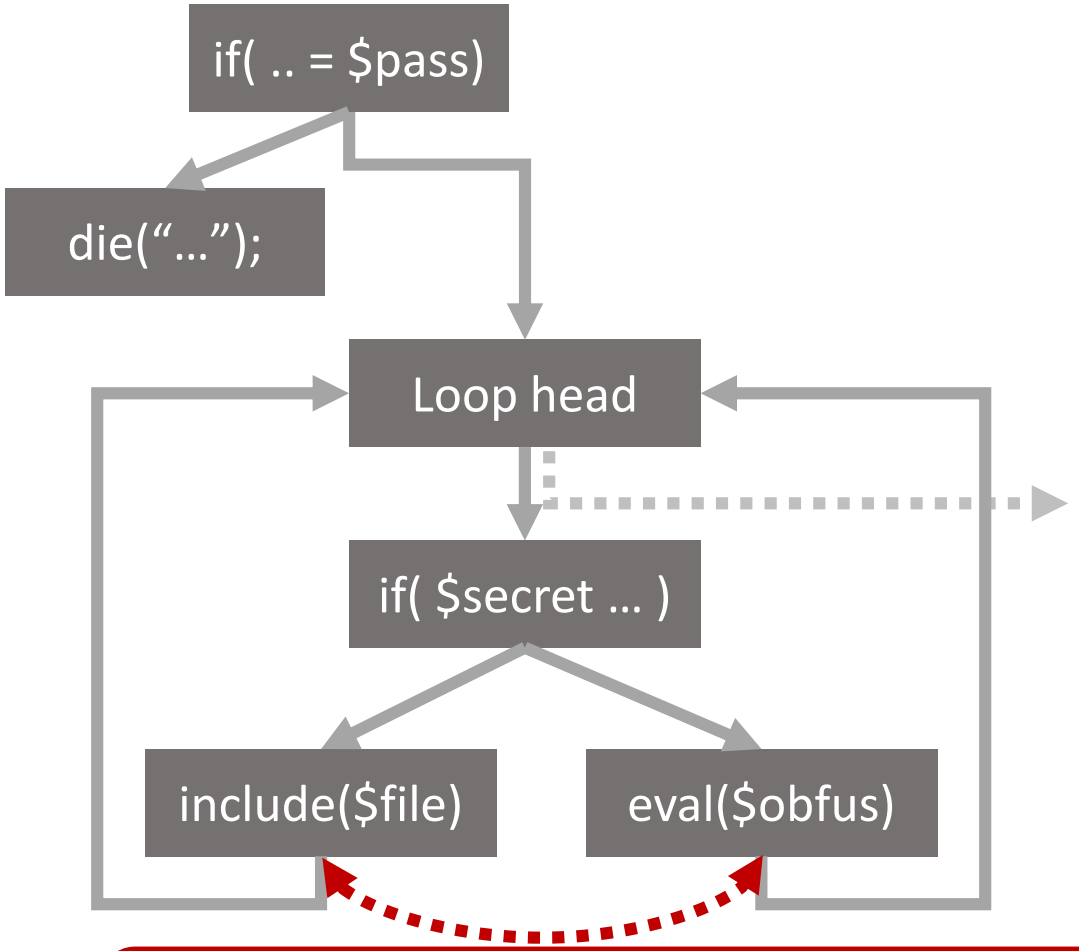
Deobfuscation in PHP,

ACSAC'19

Multiple aspects of web server malware (i.e., PHP malware)

- PHP is a dynamic language, making web development easy, so as malware development
  1. Evasive Code
     - Decide whether to run or not, depending on the context
  2. Multiple Layers of Obfuscation via Dynamic Constructs
     - Use eval and include to dynamically generate/include code
     - Obfuscation is cheap and easy in PHP
  3. Automated Variant Generation
     - Creating variants of PHP malware is easy

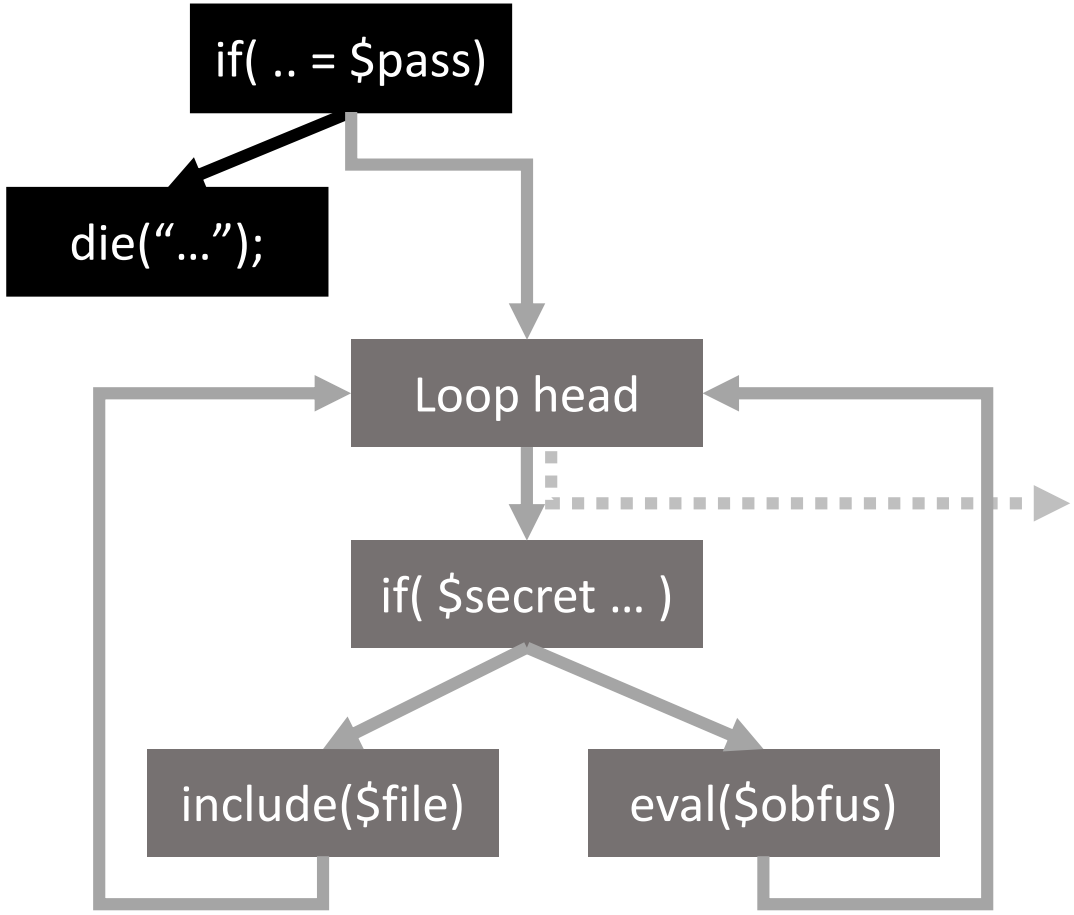
Evasive and Multiple Layers of Obfuscation




```
1  if ($_GET[1]!=$password)
2    die("Nothing to see here.");
3  for (...)
4    if ($secret === "...") {
5      include($filename);
6    } else {
7      eval($obfuscated_code);
8    }
```

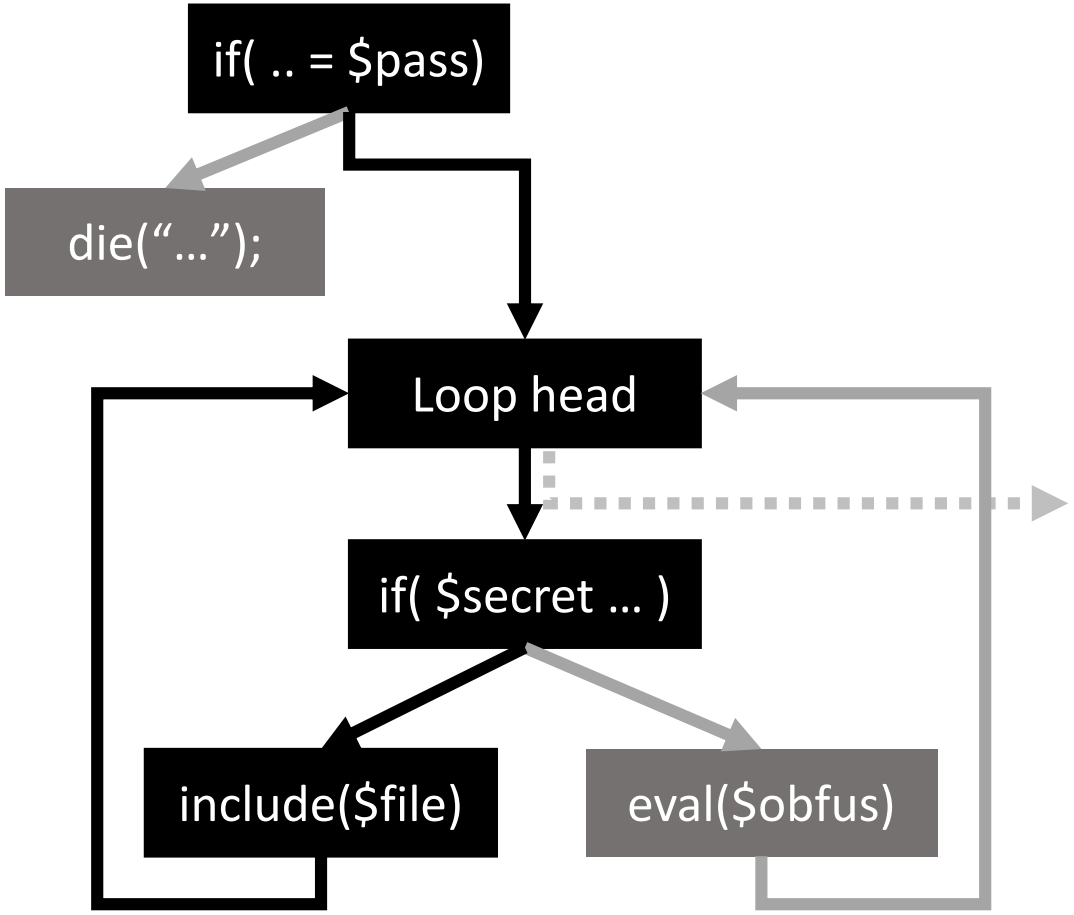
eval($obfuscated_code) defines $filename, and include($filename) will update $obfuscated_code

1. Evasive




```php
if ($_GET[1]!=$password)
  die("Nothing to see here.");
for (...)
  if ($secret === "...") {
    include($filename);
  } else {
    eval($obfuscated_code);
  }
```

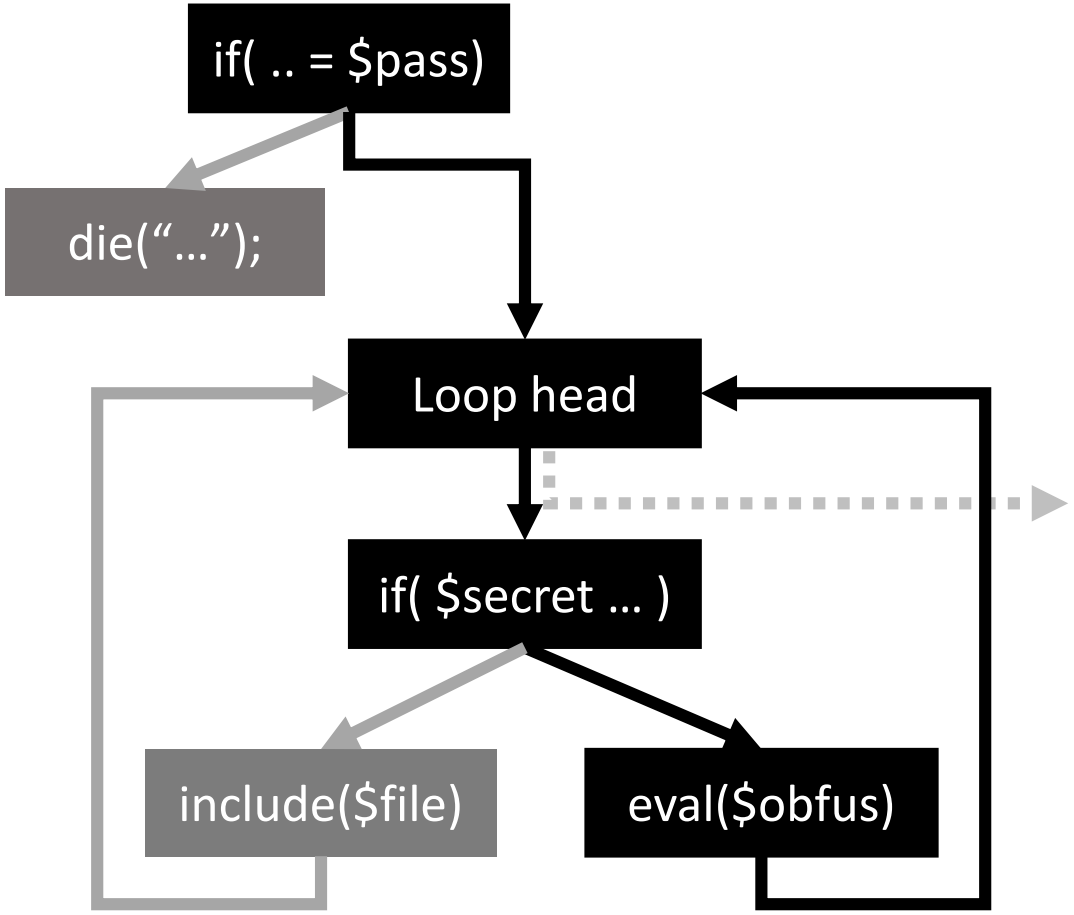
2. Multiple Layers of Obfuscation




```php
if ($_GET[1]!=$password)
  die("Nothing to see here.");
for (...)
  if ($secret === "...") {
    include($filename);
  } else {
    eval($obfuscated_code);
  }
```

No deobfuscation

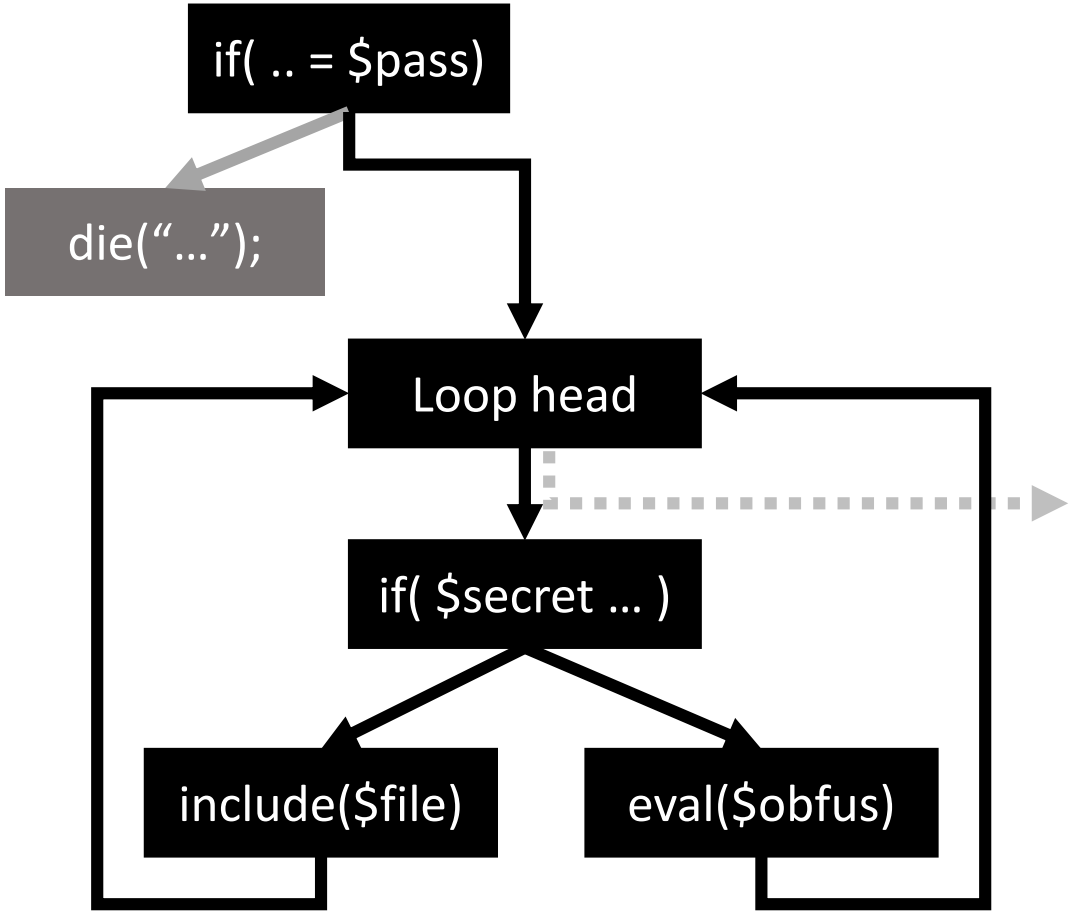
2. Multiple Layers of Obfuscation




```
1  if ($_GET[1]!=$password)
2    die("Nothing to see here.");
3  for (...)
4    if ($secret === "...") {
5      include($filename);
6    } else {
7      eval($obfuscated_code);
8    }
```

Deobfuscation Layer 1

2. Multiple Layers of Obfuscation




```
1  if ($_GET[1]!=$password)
2    die("Nothing to see here.");
3  for (...)
4    if ($secret === "...") {
5      include($filename);
6    } else {
7      eval($obfuscated_code);
8    }
```

Deobfuscation Layer 2

3. Automated Malware Variant Generation

- Creating PHP malware variants is as simple as a string manipulation

```
1  $s_pass = '4b34f78fbd22051343801156232Od47f';
2  $x=gzinflate(base64_decode("7b1pe+O4lSj8OfM88x8
   U3XpT5chVXLV1LRlKFEVt1L5QnVw/3EmJm7hTufnvL0BSsm
   zLdl...+JDlu+vGCe/m0F3+e7PpQzuf97sMYN0MIA7DsAeZ
   PX/5/"));
3  eval('?>'.$x);
```

(a) Original Malware

```
10 $s_pass = '4b34f78fbd22051343801156232Od47f';
11 eval('$x=gzin'.'flate(base'.'64_de'.'code("7b1p
   e+O4lSj8OfM88x8U3XpT5chVXLV1LRlKFEVt1L5QnVw/3Em
   Jm7hTufnvL0BSsmzLdl...+JDlu+vGCe/m0F3+e7PpQzuf9
   7sMYN0MIA7DsAeZPX/5/"));');
12 eval('?>'.$x);
```

(b) Malware Variant 1

```
20 $s_pass = 'b4616d42a983401bcf344f9c18675777';
21 eval('$x=gzi'.'nflate(ba'.'se64_dec'.'ode("7b1p
   e+O4lSj8OfM88x8U3XpT5chVXLV1LRlKFEVt1L5QnVw/3Em
   Jm7hTufnvL0BSsmzLdl...+JDlu+vGCe/m0F3+e7PpQzuf9
   7sMYN0MIA7DsAeZPX/5/"));');
22 eval('?>'.$x);
```

(c) Malware Variant 2

```
30 $s_pass = '62908bf72c21a3d8eaa23a55dec98e4b';
31 eval('$x=g'.'zin'.'fla'.'te(base6'.'4_dec'.'ode
   ("7b1pe+O4lSj8OfM88x8U3XpT5chVXLV1LRlKFEVt1L5Qn
   Vw/3EmJm7hTufnvL0BSsmzLdl...+JDlu+vGCe/m0F3+e7P
   pQzuf97sMYN0MIA7DsAeZPX/5/"));');
32 eval('?>'.$x);
```

(d) Malware Variant 3

⋮

3. Automated Malware Variant Generation

- Changing $s_pass

```
1  $s_pass = '4b34f78fbd220513438011562320d47f';
2  $x=gzinflate(base64_decode("7b1pe+O4lSj8OfM88x8
   U3XpT5chVXLV1LRlKFEVt1L5QnVw/3EmJm7hTufnvL0BSsm
   zLdl...+JDlu+vGCe/m0F3+e7PpQzuf97sMYN0MIA7DsAeZ
   PX/5/"));
3  eval('?>'.$x);
```

(a) Original Malware

```
10 $s_pass = '4b34f78fbd220513438011562320d47f';
11 eval('$x=gzin'.'flate(base'.'64_de'.'code("7b1p
   e+O4lSj8OfM88x8U3XpT5chVXLV1LRlKFEVt1L5QnVw/3Em
   Jm7hTufnvL0BSsmzLdl...+JDlu+vGCe/m0F3+e7PpQzuf9
   7sMYN0MIA7DsAeZPX/5/"));');
12 eval('?>'.$x);
```

(b) Malware Variant 1

```
20 $s_pass = 'b4616d42a983401bcf344f9c18675777';
21 eval('$x=gzi'.'nflate(ba'.'se64_dec'.'ode("7b1p
   e+O4lSj8OfM88x8U3XpT5chVXLV1LRlKFEVt1L5QnVw/3Em
   Jm7hTufnvL0BSsmzLdl...+JDlu+vGCe/m0F3+e7PpQzuf9
   7sMYN0MIA7DsAeZPX/5/"));');
22 eval('?>'.$x);
```

(c) Malware Variant 2

```
30 $s_pass = '62908bf72c21a3d8eaa23a55dec98e4b';
31 eval('$x=g'.'zin'.'fla'.'te(base6'.'4_dec'.'ode
   ("7b1pe+O4lSj8OfM88x8U3XpT5chVXLV1LRlKFEVt1L5Qn
   Vw/3EmJm7hTufnvL0BSsmzLdl...+JDlu+vGCe/m0F3+e7P
   pQzuf97sMYN0MIA7DsAeZPX/5/"));');
32 eval('?>'.$x);
```

(d) Malware Variant 3

⋮

3. Automated Malware Variant Generation

- “$x = gzinflate(base64_decode” ➔ “eval(‘$x=gzip’.’flate…”

```
1  $s_pass = '4b34f78fbd220513438011562320d47f';
2  $x=gzinflate(base64_decode("7b1pe+O4lSj8OfM88x8
   U3XpT5chVXLV1LRlKFEVt1L5QnVw/3EmJm7hTufnvL0BSsm
   zLdl...+JDlu+vGCe/m0F3+e7PpQzuf97sMYN0MIA7DsAeZ
   PX/5/"));
3  eval('?>'.$x);
```

(a) Original Malware

```
10 $s_pass = '4b34f78fbd220513438011562320d47f';
11 eval('$x=gzin'.'flate(base'.'64_de'.'code("7b1p
   e+O4lSj8OfM88x8U3XpT5chVXLV1LRlKFEVt1L5QnVw/3Em
   Jm7hTufnvL0BSsmzLdl...+JDlu+vGCe/m0F3+e7PpQzuf9
   7sMYN0MIA7DsAeZPX/5/"));');
12 eval('?>'.$x);
```

(b) Malware Variant 1

```
20 $s_pass = 'b4616d42a983401bcf344f9c18675777';
21 eval('$x=gzi'.'nflate(ba'.'se64_dec'.'ode("7b1p
   e+O4lSj8OfM88x8U3XpT5chVXLV1LRlKFEVt1L5QnVw/3Em
   Jm7hTufnvL0BSsmzLdl...+JDlu+vGCe/m0F3+e7PpQzuf9
   7sMYN0MIA7DsAeZPX/5/"));');
22 eval('?>'.$x);
```

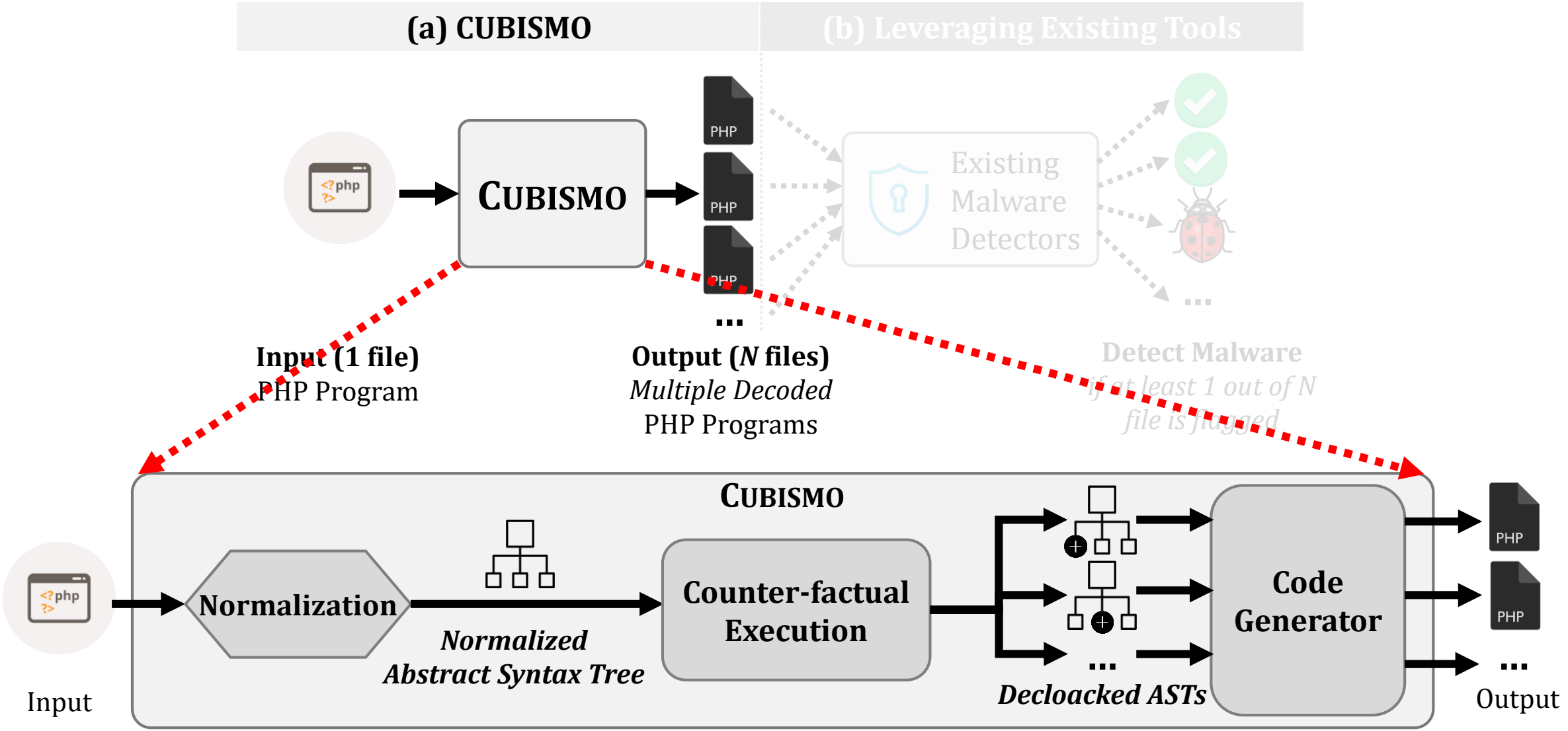
(c) Malware Variant 2

```
30 $s_pass = '62908bf72c21a3d8eaa23a55dec98e4b';
31 eval('$x=g'.'zin'.'fla'.'te(base6'.'4_dec'.'ode
   ("7b1pe+O4lSj8OfM88x8U3XpT5chVXLV1LRlKFEVt1L5Qn
   Vw/3EmJm7hTufnvL0BSsmzLdl...+JDlu+vGCe/m0F3+e7P
   pQzuf97sMYN0MIA7DsAeZPX/5/"));');
32 eval('?>'.$x);
```

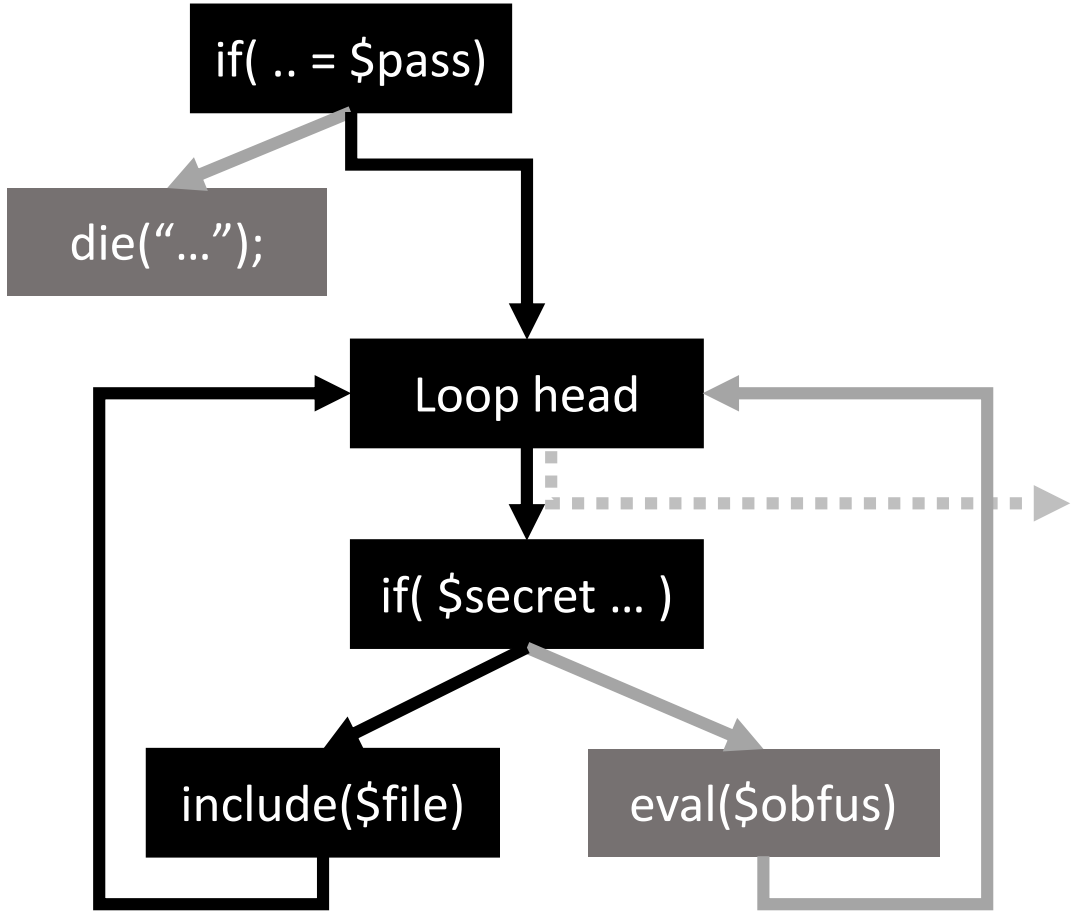
(d) Malware Variant 3

⋮

Overview: CUBISMO

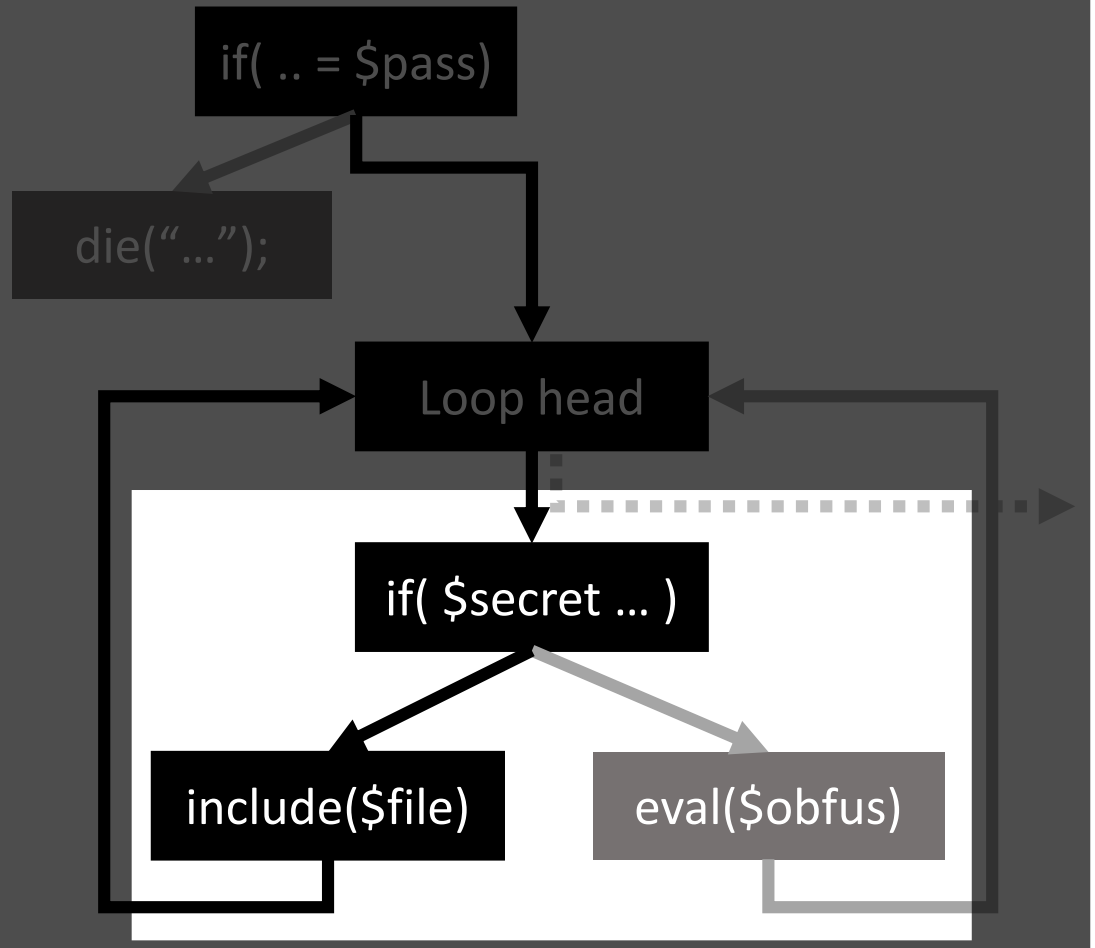


Exposing Multiple Aspects of Malware



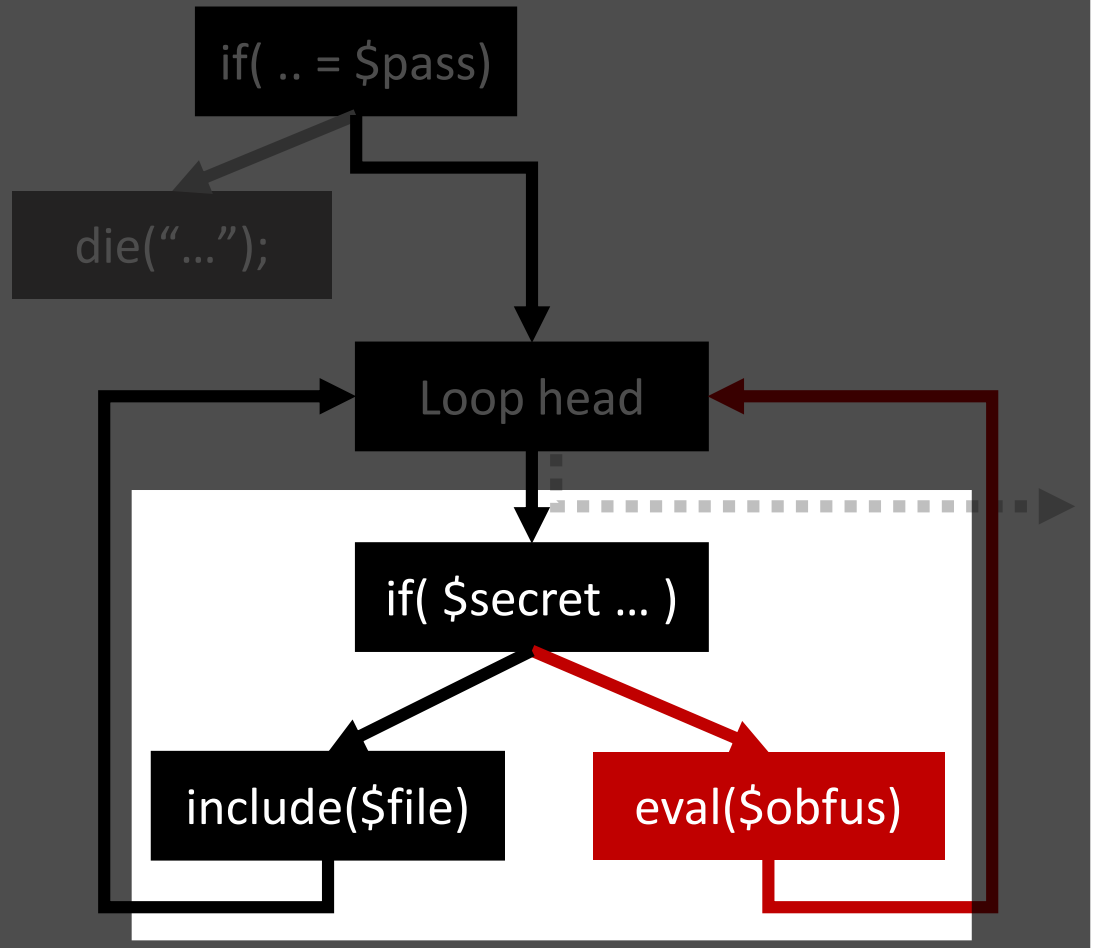

```php
if ($_GET[1]!=$password)
  die("Nothing to see here.");
for (...)
  if ($secret === "...") {
    include($filename);
  } else {
    eval($obfuscated_code);
  }
```

Counter-factual Execution [MalMax, CCS'19]




```
1  if ($_GET[1]!=$password)
2    die("Nothing to see here.");
3  for (...)
4    if ($secret === "...") {
5      include($filename);
6    } else {
7      eval($obfuscated_code);
8    }
```

Counter-factual Execution [MalMax, CCS'19]




```
1  if ($_GET[1]!=$password)
2    die("Nothing to see here.");
3  for (...)
4    if ($secret === "...") {
5      include($filename);
6    } else {
7      eval($obfuscated_code);
8    }
```

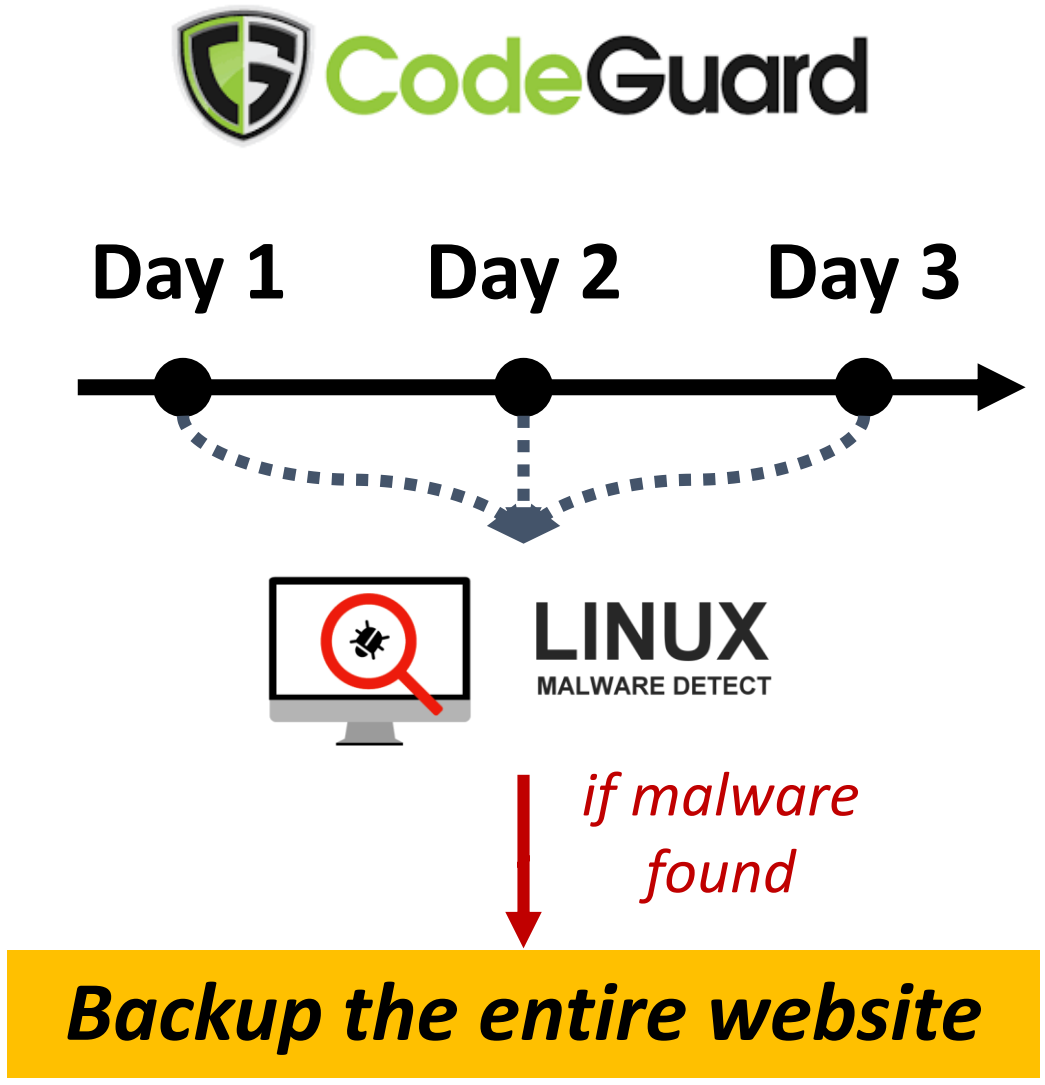
More details in the paper

- **Counter-factual Execution.** Exploring hidden malicious paths and execution contexts.
- **Sharing Global Artifacts between Paths.** Facilitating discovery of new dynamic code generation dependent on global artifacts (e.g., global variables).
- **Sandboxing**. Preventing malicious programs from harming the host system.

and more...

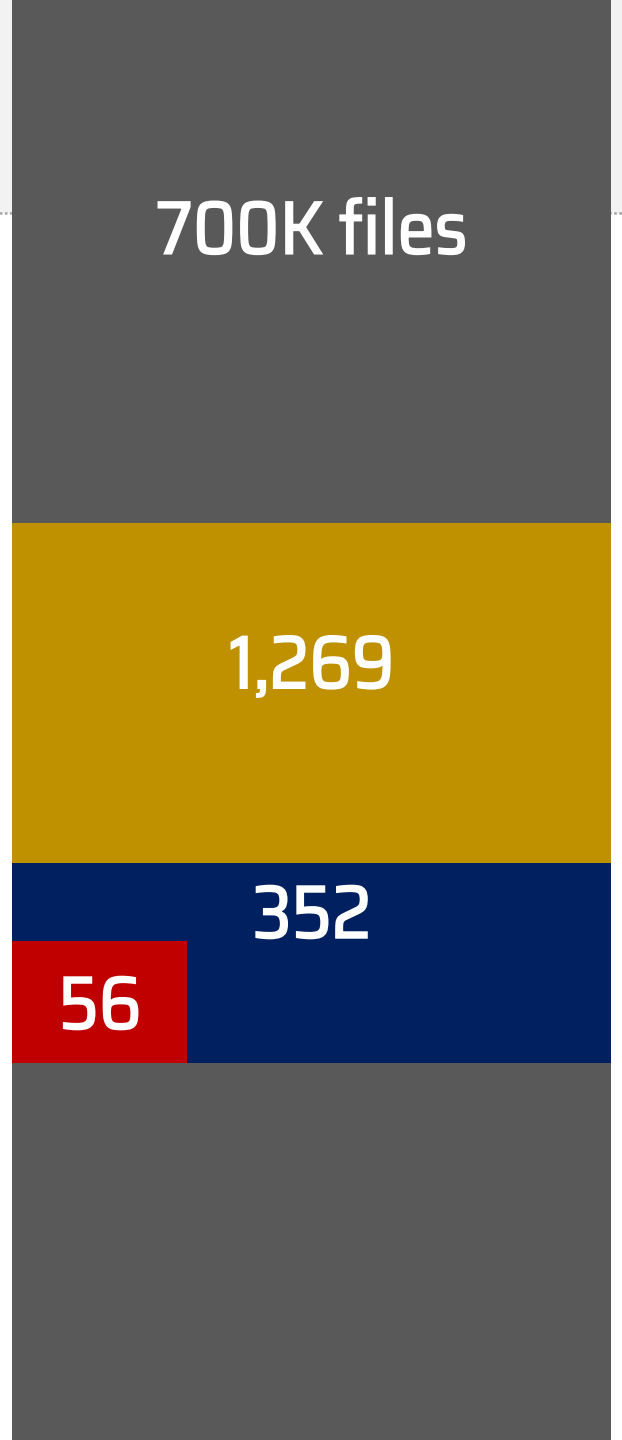
Evaluation: Dataset Collection

- Real-world Website Deployments: **400K real-world website snapshots** deployed in the wild (via **CodeGuard**).
- **Nightly Backup:** Every night, a website is backed up when maldet finds one or more malware. Multiple versions of a website can be backed up.



Evaluation: Numbers

- From **400K** website snapshots (about 3M files)
- **700K** files containing PHP code
- **1,269** files with dynamic constructs (potentially obfuscated)
  - **1,040** unique files.
- We scan them with VirusTotal: **688** files were detected.
- We manually analyze the remaining **352** files left undetected (with our previous work in CCS'19)
- Identified **56** previously undetected malware
- **CUBISMO can reveal 53 out of the 56 malware samples**

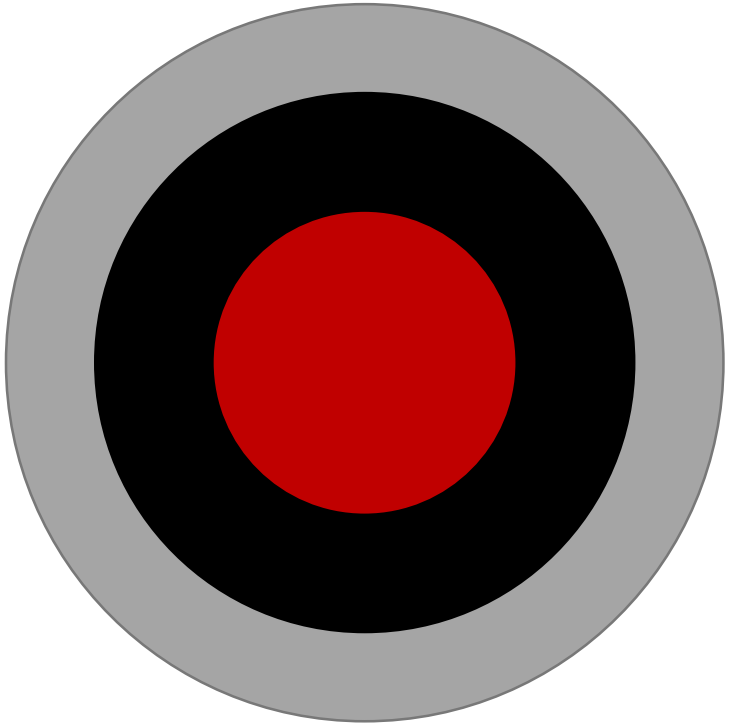


Evaluation: Methodology

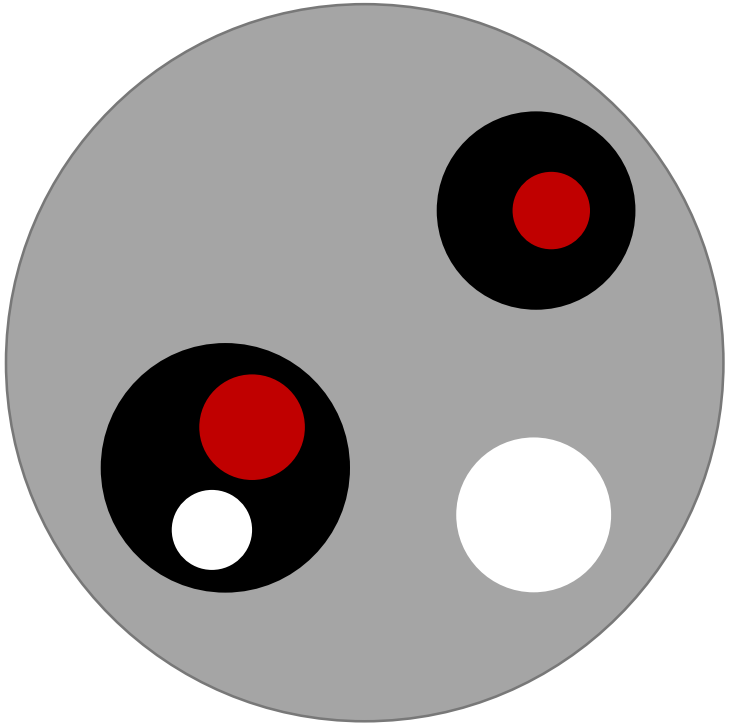
- We use **VirusTotal** (as an existing tool in our pipeline)
  - We feed malware to CUBISMO that produces multiple decloaked files
  - (a) We feed the decloaked files to VT
  - (b) We also feed the original file to VT
    and then we compare (a) and (b)
- **VirusTotal learns**! and we consider that
  - After a few days of our submissions, VT starts to detect what they did not detect
  - Our experiments are less likely affected by this, because for each submission, we submit all the files generated from an original sample within a minute.

Evaluation: Why Though?

- Do Multiple Layers of Obfuscation Matter?
- Why not simply deobfuscate everything and then scan?

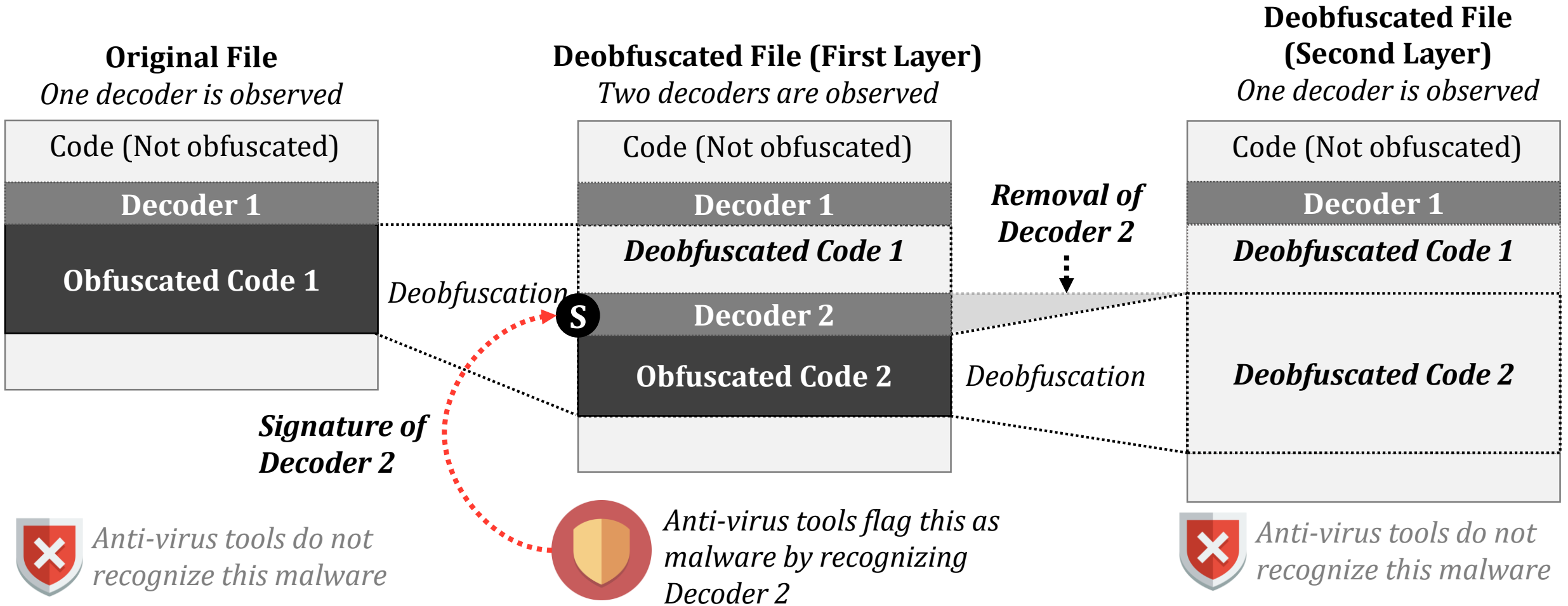


Naive Obfuscation



Advanced Obfuscation

Evaluation: Every Layer Matters



Evaluation: Everything Matters

	Orig.	Norm.	Layer 1	Layer 2	Layer 3	Layer 4
m1	0	1	2	–	–	–
m2	0	0	1	1	1	2
m3	0	0	1	–	–	–
m4	0	0	1	–	–	–
m5	0	0	1	1	–	–
m6	0	0	1	–	–	–
m7	0	0	1	1	–	–
m8	0	0	1	–	–	–
m9	0	0	1	–	–	–
m10	0	1	1	–	–	–
m11	0	0	3	1	–	–
m12	0	0	1	–	–	–
m13	0	0	1	–	–	–
m14	0	1	3	1	–	–
m15	0	0	1	–	–	–
m16	0	0	1	1	–	–
m17	0	0	0	0	–	–
m18	0	0	1	–	–	–
m19	0	1	1	–	–	–
m20	0	0	1	1	1	–
m21	0	0	1	5	–	–
m22	0	0	2	2	–	–
m23	0	0	1	–	–	–
m24	0	0	1	–	–	–
m25	0	0	3	–	–	–
m26	0	0	1	1	–	–
m27	0	0	0	0	–	–
m28	0	0	1	–	–	–

	Orig.	Norm.	Layer 1	Layer 2	Layer 3	Layer 4
m29	0	0	1	1	1	–
m30	0	0	1	–	–	–
m31	0	0	1	–	–	–
m32	0	0	1	–	–	–
m33	0	1	3	1	–	–
m34	0	0	1	1	0	1
m35	0	0	1	–	–	–
m36	0	1	1	–	–	–
m37	0	0	1	–	–	–
m38	0	1	1	–	–	–
m39	0	0	1	–	–	–
m40	0	0	3	1	3	3
m41	0	1	1	–	–	–
m42	0	1	1	–	–	–
m43	0	0	1	1	1	–
m44	0	0	1	1	–	–
m45	0	0	1	1	1	1
m46	0	0	1	–	–	–
m47	0	0	1	–	–	–
m48	0	0	1	–	–	–
m49	0	0	1	1	–	–
m50	0	0	0	–	–	–
m51	0	0	1	–	–	–
m52	0	0	1	–	–	–
m53	0	1	2	1	–	–
m54	0	0	1	–	–	–
m55	0	0	1	–	–	–
m56	0	0	1	–	–	–

Evaluation: Details

- **False positive**: We test 100 benign PHP files with obfuscations (they do that to protect their code) and 200 benign PHP files from benign PHP applications.

- **Performance**: Decloaking process will be adding ~130% runtime overhead. We can parallelize the technique to improve the performance. Details in paper.

- And more in the paper.

Limitations

- Normalization would miss malicious code hidden in comments.

```
1  <?php
2  namespace A {
3    class ClassA {
4      function funcA() {
5        $f = basename(__FILE__, '.php');
6        extract_malicious_code( $f );
7      }
8    }
9  }
10 namespace {
11   $a = new \A\ClassA();
12   ...
13 }
14 // Comment including malicious code
15 // Comment to break parser
```

(a) Original Program
(PHP-Parser Crash)

Normalization

```
1  <?php
2  namespace A {
3    class ClassA {
4      function funcA() {
5        $f = basename(__FILE__, '.php');
6        extract_malicious_code( $f );
7      }
8    }
9  }
10 namespace {
11   $a = new \A\ClassA();
12   ...
13 }
14
```

(b) Normalized Program
(No Crash)

Thanks!

- CUBISMO is publicly available: https://cubismo.s3.amazonaws.com/cubismo.html

- Sponsors:
  - AFRL (FA8750-17-S-7007)
  - NSF (1916499 and 1850392)
  - CodeGuard