# Obfuscation by Partial Evaluation of Distorted Interpreters

**Neil D. Jones**
DIKU, University of Copenhagen (prof. emeritus)

Joint work with **Roberto Giacobazzi** and **Isabella Mastroeni**
University of Verona

**Paper: in PEPM 2012**

# WHAT AND WHY ?

**Obfuscation = hiding of intended meaning in communication, making a program confusing, wilfully ambiguous, and harder to interpret.**

- **Making something dark**
- **Putting something in a shadow**

**Our version: a semantics-preserving program transformation intended to make transformed programs hard to understand.**

**Popular in the computer security and software engineering communities: Obfuscation, Watermarking, Steganography. WHY ?**

- **To avoid theft of an algorithm (hard to steal or adapt or patent)**
- **to hide evidence in a program of its authorship, ownership, creator**
- **. . . related other security techniques . . .**

# OBFUSCATION = A PROGRAM TRANSFORMATION $\mathtt{p} \mapsto \mathtt{p}'$

**A scenario:**

- **An attacker is trying to analyze or decipher obfuscated program $\mathtt{p}'$**
- **a defender is trying to construct $\mathtt{p}'$ to make this hard to do**

**Want: $\mathtt{p}'$ is executable, but it should be hard to adapt, exploit, or analyze.**

**SOME CRITERIA:**

1. **Semantics preservation: we must have**

$$\forall \mathtt{p} \,.\, [\![\mathtt{p}']\!] = [\![\mathtt{p}]\!]$$

2. ***Automation*: $\mathtt{p}'$ is obtained from $\mathtt{p}$ without hand work.**

   **Thus the programmer/inventor of $\mathtt{p}$ can release $\mathtt{p}'$ instead of $\mathtt{p}$.**

3. ***Efficiency*: $\mathtt{p}'$ should not be too much slower or larger than $\mathtt{p}$.**

4. ***Potency* = hard reverse engineering, namely**

   **$\mathtt{p}$ is hard to obtain from its obfuscated version $\mathtt{p}'$.**

# HOW ? OUR SILVER BULLET

**Program transformation by specializing a self-interpreter.**

**Program** `interp` **is a *self-interpreter* if for all programs** `p` **and data** $\mathtt{d} \in \mathbb{D}$

$$[\![\mathtt{p}]\!](\mathtt{d}) = [\![\mathtt{interp}]\!](\mathtt{p},\mathtt{d})$$

**A *partial evaluator* (or *program specializer*)** `spec` **satisifies for every program** `p` **with "static" input** $\mathtt{s} \in \mathbb{D}$ **and "dynamic" input** $\mathtt{d} \in \mathbb{D}$**, that**

$$[\![\mathtt{p}]\!](\mathtt{s},\mathtt{d}) = [\![\ [\![\mathtt{spec}]\!](\mathtt{p},\mathtt{s})\ ]\!](\mathtt{d})$$

**Some practical program specializers:**
TEMPO **and** CMIX **for C;** ECCE **and** LOGEN **for Prolog;** UNMIX, SIMILIX **and** PGG **for** SCHEME**.**

**We used Unmix in our experiments.**

# PROGRAM TRANSFORMATION BY INTERPRETER SPECIALIZATION

**Suppose**

$$\mathtt{p}' := [\![\mathtt{spec}]\!](\mathtt{interp}, \mathtt{p})$$

**So $\mathtt{p}'$ is the result of specializing a self-interpreter to program $\mathtt{p}$.**

**Claim: $[\![\mathtt{p}]\!] = [\![\mathtt{p}']\!]$, by simple equational reasoning. For any data $\mathtt{d}$,**

$$\begin{array}{lll} [\![\mathtt{p}]\!](\mathtt{d}) & = [\![\mathtt{interp}]\!](\mathtt{p}, \mathtt{d}) & \text{definition of self-interpreter} \\ & = [\![[\![\mathtt{spec}]\!](\mathtt{interp}, \mathtt{p})]\!](\mathtt{d}) & \text{definition of specializer} \\ & = [\![\mathtt{p}']\!](\mathtt{d}) & \text{definition of } \mathtt{p}' \end{array}$$

**Therefore the function**

$$\mathtt{p} \mapsto [\![\mathtt{spec}]\!](\mathtt{interp}, \mathtt{p})$$

**is a *semantics-preserving program transformer*.**

# OPTIMAL SPECIALIZATION VERSUS OBFUSCATION

**In the transformation**

$$\mathtt{p} \mapsto \mathtt{p}' = [\![\mathtt{spec}]\!](\mathtt{interp}, \mathtt{p})$$

**For optimal specialization:**

$\mathtt{p}'$ **should be as efficient as** $\mathtt{p}$**.**

**But... for good obfuscation:**

$\mathtt{p}'$ **should be harder to understand than** $\mathtt{p}$**.**

**Conflicting goals, but achievable by (re-)designing** `interp` **cleverly.**

**We show that several useful program obfuscations can be obtained by interpreter specialization.**

**A bit of useful slack:**

> **It is OK for** `interp` **to be slow, as long as**
>
> $\mathtt{p}'$ **is fast enough, and hard enough to understand.**

# IN GENERAL, IF $\mathtt{p}' = [\![\mathtt{spec}]\!](\mathtt{interp}, \mathtt{p})$:

1. **Program $\mathtt{p}'$ inherits the *algorithm* of program $\mathtt{p}$.**
2. **Program $\mathtt{p}'$ inherits the *programming style* of $\mathtt{interp}$.**

**Our trick: build a *program transformer***

- **by programming a self-interpreter $\mathtt{interp}^+$**
- **in a style to give the desired transformation.**
- **Then (automatically)**
  - **specialise $\mathtt{interp}^+$ to any input program $\mathtt{p}$**
  - **to transform $\mathtt{p}$ as desired.**

**Some writing styles that can be inherited from $\mathtt{interp}$:**

- **functional language, tail-recursive ,or CPS (continuation-passing) styles**
- **Or $\mathtt{interp}$ can use memoisation to implement function calls.**

# STRUCTURE OF A SIMPLE SELF-INTERPRETER

```
input p, d;                                   Program to be interpreted, and its data
pc := 2;                                      Initialise program counter
store := [in ↦ d, out ↦ 0, x1 ↦ 0, ...];      Initialise store
 while pc < length(p) do
      instruction := lookup(p, pc);           Find the pc-th instruction
      case instruction  of                    Dispatch on syntax
      skip     :  pc := pc + 1;               Once case per command type
      x := e   :  store := store[x ↦ eval(e, store)]; pc := pc + 1;
      ...   endw ;
output store[out];
eval(e, store)  =  case e of                  Function to evaluate expressions
      constant : e
      variable  : store(e)
      e1 + e2   : eval(e1, store) + eval(e2, store)
      e1 − e2   : eval(e1, store) − eval(e2, store)
      e1 ∗ e2   : eval(e1, store) ∗ eval(e2, store)
      ...
```

# SPECIALIZATION OF THE SIMPLE SELF-INTERPRETER

**A simple color-coding scheme:**

- **GREEN for static(ally computable)**
- **RED for dynamic.**

**First steps using this coding:**

- `interp` **variable** `p` **is classified as "static", and variable** $d$ **is classified as "dynamic".**
- **. . . and a bit more:**
- 
- `interp` **variables** $e, pc$ **and** $instruction$ **are classified as "static", since given any** `p` **they can only assume finitely many values.**

# STRUCTURE OF A SIMPLE SELF-INTERPRETER

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      x:=e  :  store := store[x ↦ eval(e, store)]; pc:=pc+1;
      ...   endw ;
output store[out];
eval(e, store)  =  case e of Function to evaluate expressions
      constant : e
      variable  : store(e)
      e1 + e2   : eval(e1, store)+eval(e2, store)
      e1 - e2   : eval(e1, store)−eval(e2, store)
      e1 * e2   : eval(e1, store)*eval(e2, store)
      ...
```

# SPECIALIZATION OF THE SIMPLE SELF-INTERPRETER

- `interp` **variable** `p` **is classified as "static", and variable** $d$ **is classified as "dynamic".**
- `interp` **variables** $e, pc$ **and** $instruction$ **are classified as "static", since given any** `p` **they can only assume finitely many values.**
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- **The interpreter's** `while` **loop is unfolded, so the only remaining control transfers implement the transfers in program** `p`**.**

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- `interp` **variables** $e, pc$ **and** $instruction$ **are classified as "static", since given any** `p` **they can only assume finitely many values.**
- **The interpreter's** `while` **loop is unfolded, so the only remaining control transfers correspond to those present in program** `p`**.**
- `interp` **function** $eval$ **is completely unfolded and so does not appear in** $\mathtt{p}'$**, since all recursive calls decrease the static value** $e$**.**

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# SPECIALIZATION OF THE SIMPLE SELF-INTERPRETER

- `interp` **variable** `p` **is classified as "static", and variable** $d$ **is classified as "dynamic".**
- `interp` **variables** $e, pc$ **and** $instruction$ **are classified as "static", since given any** `p` **they can only assume finitely many values.**
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- **The interpreter's** `while` **loop is unfolded, so the only remaining control transfers correspond to those present in program** `p`**.**
- 
- `interp` **function** $eval$ **is completely unfolded and so does not appear in** $\mathtt{p}'$**, since all recursive calls decrease the static value** $e$**.**
- `interp` **variable** $store$ **is a function with static domain but dynamic range.**
- **"Arity raising" splits** $store$ **into: one specialised program variable for each of** `p`**'s variables.**

# SPECIALIZATION OF THE SIMPLE SELF-INTERPRETER

**Net effect of all of these tricks:**

**– the specialized program** $\mathtt{p}' = [\![\mathtt{spec}]\!](\mathtt{interp}, \mathtt{p})$

**– is identical to** $\mathtt{p}$ **(up to variable renaming).**

**Alas, this is not what we want for obfuscation**

**since** $\mathtt{p}'$ **is** $\alpha$**-equivalent to** $\mathtt{p}$

**(identical up to renaming** $=$ **too easy to deobfuscate. . .)**

**But it is a first step towards**

**more interesting automatic program transformation**

# AN EASY EXAMPLE: DATA OBFUSCATION

**Data obfuscation** Similar to Drape's 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 $dob(x)$.

**Modify `interp` so that:**

- All stored values are obfuscated;
  - Input values are obfuscated in the initial store;
  - variable values are obfuscated just before putting in the store; and
  - output values are de-obfuscated in the program's final store.
- Expression evaluation yields obfuscated values:

# A VERY SIMPLE DATA OBFUSCATION: $V \mapsto 2V$

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

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

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

**while** $pc < length(\mathrm{p})$ **do**

  $instruction := lookup(\mathrm{p}, \mathrm{pc})$;

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

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

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

  ... **endw** ;

output $\textbf{dob}(store[out])$;

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

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

  constant : $\textbf{obf}(e)$

  variable : $store(e)$ — Variable values

  e1 + e2 : $\textbf{obf}(\textbf{dob}(eval(e1, store)) + \textbf{dob}(eval(e2, store)))$

  e1 - e2 : $\textbf{obf}(\textbf{dob}(eval(e1, store)) - \textbf{dob}(eval(e2, store)))$

# EXAMPLE OUTPUT FROM DATA OBFUSCATION

**Program** p

```
1. input x;
2. y := 2;
3. while x > 0 do
       4. y := y + 2;
       5. x := x − 1
   endw
6. output y;
7. end
```

**is automatically transformed into this equivalent obfuscated program** p′**:**

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

# WHAT IS HAPPENING ? HOW TO GENERALISE ?

1. **The above example applies one-to-one functions**

$$Value \underset{\lambda\, x\, .\, x/2}{\overset{\lambda\, x\, .\, 2x}{\rightleftarrows}} Value$$

2. **More generally: apply one-to-one functions**

$$Value \underset{dob}{\overset{obf}{\rightleftarrows}} Value$$

3. **Still more generally: apply one-to-one store transformations:**

$$Store \underset{dob}{\overset{obf}{\rightleftarrows}} Store$$

**A nasty example:**

$$obf(x, y) = (x + y, x - y)$$

$$dob(u, v) = ((u + v)/2, (u - v)/2)$$

**This mixes up values of different variables!**

# OBFUSCATION: $(X, Y) \mapsto (U, V) = (X + Y, X - Y)$

## Program p

```
1. input x;
2. y := 2;
3. while x > 0 do
       4. y := y + 2;
       5. x := x − 1
   endw
6. output y;
7. end
```

## is automatically transformed into this equivalent obfuscated program p′:

```
1. input x; u := x + y; v := x − y;          Initialise
2.1. u := (u + v)/2 + 2;                     Obfuscated y := 2
2.2. v := (u + v)/2 − 2                      -continued-
3. while (u + v)/2 > 0 do                    De-obfuscated x > 0
       4. u := u + 2; v := v − 2;
       5. u := u − 1; v := v − 1;
   endw
6. output (u − v)/2;                         De-obfuscate output
7. end
```

# OBFUSCATION FROM A "WHOLE-PROGRAM" VIEWPOINT

**A conflict that makes program obfuscation a subtle problem concerns a general principle in programming:**

***Good programs are well-structured and have concise invariants*.**

**This is a key to**

- **understanding a program, and**
- **adapting it to new purposes.**

**Good structure and short invariants are necessity in order to develop, debug and perfect a program `p` in the first place.**

**However, instead *an obfuscated program***

***should not be well-structured and***
***should not be easy to understand*.**

**This suggests (among other things):**

**obfuscation by making the program's control flow hard to understand.**

# EXAMPLE OF CODE FLATTENING

The following flattened program $\mathtt{p}'$ has

- only one loop (regardless of how many loops $\mathtt{p}$ has), and
- an explicit program counter $pc$

What has been obfuscated? The flow of control!

**Original program $\mathtt{p}$:**

$^{1.}$**input** $x$;
$^{2.}y := 2$;
$^{3.}$**while** $x > 0$ **do**
  $^{4.}y := y + 2$;
  $^{5.}x := x - 1$
**endw**
$^{6.}$**output** $y$;
$^{7.}$**end**

**Flattened equivalent program $\mathtt{p}'$:**

$^{1.}$**input** $x$; $^{2.}pc := 2$;
$^{3.}$**while** $pc < 6$ **do**
  $^{4.}$**case** $pc$ **of**
    $2:$ $^{5.}y := 2$; $^{6.}pc := 3$;
    $3:$ $^{7.}$**if** $x > 0$ **then** $^{8.}pc := 4$ **else** $^{9.}pc := 6$;
    $4:$ $^{10.}y := y + 2$; $^{11.}pc := 5$;
    $5:$ $^{12.}x := x - 1$; $^{13.}pc := 3$;
  **endw**
$^{14.}$**output** $y$
$^{15.}$**end**

# SPECIALIZATION OF THE "FLATTENING" INTERPRETER:

**Essential trick: to recode `interp` so that the specializer will classify variable $pc$ as *dynamic*. Technically**

- **$pc$ is made dynamic using the Unmix `generalize` annotation.**
- **`interp` is extended to have both dynamic and static copies of $pc$, so specialization will generate `p`′ code such as**

$$\textbf{case}\ldots\ pc = 5:\ \ x := x - 1; pc := 3$$

- **Since $pc$ is dynamic, the while loop in $\texttt{interp}^{\texttt{flat}}$ will not be unfolded, and so $pc$ comes to appear in the specialized program `p`′.**

**The transformation**

$$\texttt{p} \mapsto \texttt{p}' = [\![\texttt{spec}]\!](\texttt{interp}^{\texttt{flat}}, \texttt{p})$$

**will flatten *any* program; i.e., it is in no way specific to the example program `p` above.**

# WHAT IS "HARD ENOUGH" ?

- **Ideally, the *complexity* of obtaining $\mathtt{p}$ from $\mathtt{p}'$ should be high (for example, NP-hard).**

  **View: the attacker is an arbitrary PTIME program.**

  **We don't know how to do this (one-way functions...).**

  **So we settle for an easier solution:**

- **Obfuscate so that $\mathtt{p}'$ is hard to abstractly interpret.**

  **View: the attacker is a program analyzer, e.g., as used in a compiler.**

  **We know better how to do this:**

  - **Use the concept of *complete abstract interpretation***
    **(studied by Giacobazzi et al)**
  - **Design self-interpreter `interp` so that the abstract interpretation of $\mathtt{p}'$ is not complete (whether or not analysis of $\mathtt{p}$ would be complete)**

# SIGN ANALYSIS: COMPLETENESS AND INCOMPLETENESS

**Abstract lattice for sign analysis:** $\{\bot, +, 0, -, \top\}$

**Sign analysis is complete for multiplication $*$: exact analysis information.**

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

**Sign analysis is incomplete for addition $+$: imprecise analysis inform'n.**

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

**Our trick: let the interpreter evaluate $*$ using $+$**

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

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

**e1 * e2** : **let** $v1 = eval(e1, store), v2 = eval(e2, store)$

**in** $v1 * (v2 - 1) + v1$ **The $+$ makes analysis imprecise!**

# OBFUSCATION BY EXPLOITING INCOMPLETENESS

**Program** $\mathrm{p}$ — **Sign analysis of** $\mathrm{p}$ **yields** $y \mapsto +$ **in**

```
1. input x;
2. y := 2;
3. while x > 0 do
       4. y := [y * y];
       5. x := x − 1
   endw
6. output y;
7. end
```

**is automatically transformed into this equivalent obfuscated program** $\mathrm{p}'$**:**

```
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;
7. end
```

**Sign analysis of** $\mathrm{p}'$ **yields** $y \mapsto \top$**.**

# EXAMPLE: ATTACK MODEL FOILED BY FLATTENING

**In the paper, we show the control flow flattening-based obfuscation can be modeled as making incomplete an abstract interpretation.**

**The attacker is an abstract interpretation extracting the program's control flow graph.**
**CFG extraction be done several abstraction steps:**

- **In input we lose the control flow when the program counter is dynamic, namely when it is controlled in the program itself,**
- **In output we lose the memory and the history of computations (traversed branches).**
- **An enriched concrete semantics yields a flow chart modeling the history of the computation.**
- **An abstraction of this concrete semantics yields a flow chart for any program.**

**Result: this (natural) abstract interpretation is incomplete for a flattened program.**

# META-LEVEL DISCUSSION

**The Futamura projections are as follow for a distorted interpreter $\texttt{interp}^{+}$:**

1. $\texttt{p}' := [\![\texttt{spec}]\!](\texttt{interp}^{+}, \texttt{p})$ **Obfuscate one program**
2. $\texttt{comp} := [\![\texttt{spec}]\!](\texttt{spec}, \texttt{interp}^{+})$ **Generate a stand-alone obfuscator**
3. $\texttt{cogen} := [\![\texttt{spec}]\!](\texttt{spec}, \texttt{spec})$ **A generator of obfuscators**

**The *example obfuscating transformations* we have seen are instances of the 1st Futamura projection.**

**2nd Futamura projection: if $\texttt{P}$ is $\texttt{interp}^{\texttt{flat}}$, then $\texttt{compiler}$ is a *stand-alone obfuscator*: a "flattening" program transformer.**

**We have done all three using the UNMIX specializer.**

# IMMEDIATE CONSEQUENCES OF FUTAMURA PROJ'S

**There are other better ways to obfuscate and to produce a obfuscator:**

- $\mathtt{p}' = [\![\mathtt{comp}]\!](\mathtt{p})$ **(obfuscate by compiler) and**
- $\mathtt{comp} = [\![\mathtt{cogen}]\!](\mathtt{interp}^{+})$ **(generate obfuscator).**

**Future developments will involve gaining a deeper understanding in expected time factors: the relations among**

1. $time_{\mathtt{p}'}(\mathtt{d})$ **and** $time_{\mathtt{p}}(\mathtt{d})$**: the slowdown imposed by the obfuscation;**
2. $time_{\mathtt{spec}}(\mathtt{interp}^{+}, \mathtt{p})$ **and** $length(\mathtt{p})$**: the amount of time to do the obfuscation by general specialization;**
3. $time_{\mathtt{comp}}(\mathtt{p})$ **and** $length(\mathtt{p})$**: the amount of time to do the obfuscation by running a generated obfuscator (significantly less than above).**

# ANOTHER TYPE OF OBFUSCATION

**A conflict that makes program obfuscation a subtle problem concerns a general principle in programming:**

***Good programs are well-structured and have concise invariants*.**

**This led to flattening, to:**

**obfuscation by making the program's control flow hard to understand.**

**There is another direction to attack the problem:**

**obfuscation by making the program's invariants and data flow hard to understand.**

**A next step: insertion of opaque predicates . Trick: replace command** `C` **by**

```
if always-false-test then junk-commands else C
```

**Point: the inserted test and** `then`**-branch code will (barely) affect the program execution. But they will complicate life for a program attacker that does not know the program's semantics.**

# SUMMING UP

1. Nice (from my viewpoint): program obfuscation provides a motive to do automatic program transformation
2. Different criteria for success from traditional program transformation:
   - not for increased efficiency,
   - not to compile, i.e., to change the programming language;
   - but to make programs hard to understand or adapt by other people (or by their automated program attack systems)
3. Partial evaluation provides a well-developed approach to do automatic program transformation
4. Starting point: a "vanilla" self-interpreter for the source language
5. This is then distorted, so its specialization to a clear-text source program will produce a computationally equivalent and correct but harder-to-understand target program.
6. Examples: data distortion; flattening; inserting opaque predicates.

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# QUESTIONS ?