SSPREW 2017 Training

Breaking Obfuscated Programs with Symbolic Execution

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Chair of Software Engineering
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Outline

Assumptions and Tools for Hands-on Tutorial

- We assume you have Docker installed and have basic user knowledge
- Docker installation instructions
  `https://docs.docker.com/engine/installation/`
- Docker image based on Ubuntu contains: Tigress, KLEE, STP, Z3, SatGraf, etc.

```
$ docker pull banescusebi/obfuscation-symex
$ docker run -it banescusebi/obfuscation-symex
```

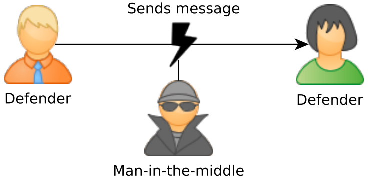
- For instructions on how to start the Docker image read description at `https://hub.docker.com/r/banescusebi/obfuscation-symex/`
- Instructions for running GUI apps available for Ubuntu and Mac OS (not mandatory, only needed for SatGraf)

Expected Outcome

After this training you will have a better understanding of the following:

- The theory and practice of obfuscation and software diversity
- Practical static & dynamic obfuscation transformations
- Tools for applying symbolic execution on obfuscated programs
- Which obfuscation transformations help against symbolic execution

1. **Man-in-the-middle (MITM)** attacks communication channels



Attackers in Computer Security

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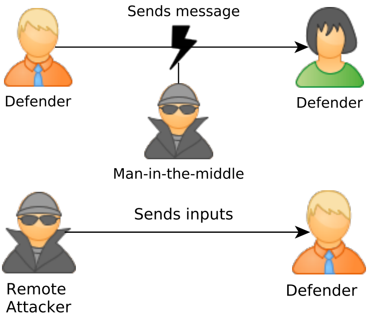
2. **Remote attacker** exploits vulnerabilities (e.g. buffer overflows)



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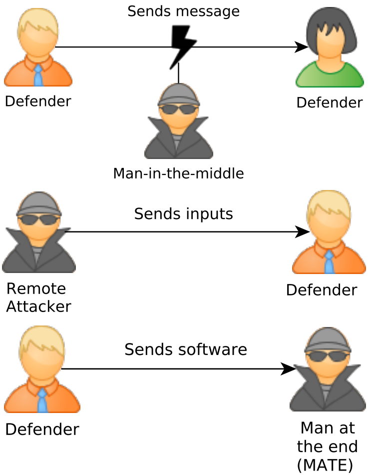

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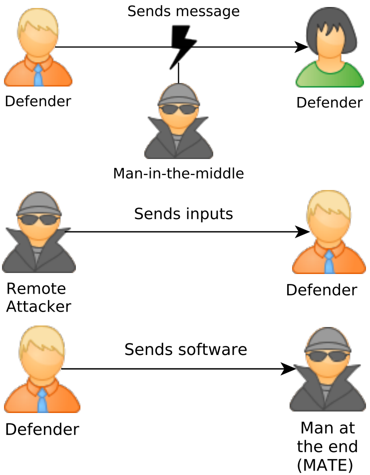

We focus on **MATE** during this tutorial.

Introduction

Informal Definition of Obfuscation:

To obfuscate a program P means to transform it into a executable program P' from which it is harder to extract information than from P.

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Popular questions:

- Wasn't obfuscation proved to be impossible back in 2001?
- Isn't obfuscation the same as security by obscurity?

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Black Box Obfuscation

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A probabilistic algorithm O is an obfuscator if the following conditions hold:

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- The memory size increase and execution slowdown of $O(P)$ w.r.t. P are less than polynomial
- Any probabilistic polynomial time attacker only has a negligible probability of guessing any bit of information about P, given $O(P)$

Obfuscated Program X

vs.

Black-Box version of Program X

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  - If the attacker only has black box access to C and D, then the probability of a successful attack is negligible
- This proof does not imply that every obfuscator fails on a **subset** of programs
- There may exist non-black-box obfuscators for some programs that leak bits of information, but are "good enough"

Indistinguishability Obfuscation

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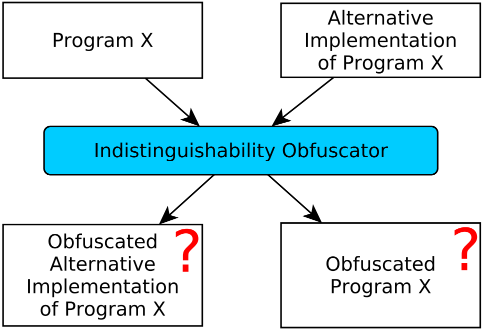
  - The obfuscated versions of 2 semantically equivalent programs cannot be distinguished



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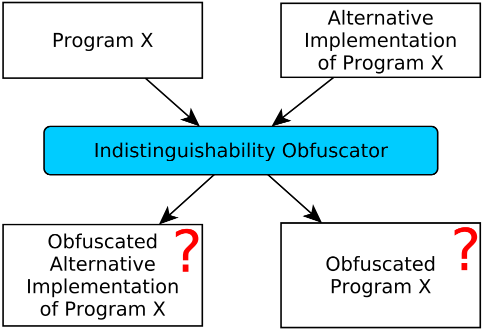

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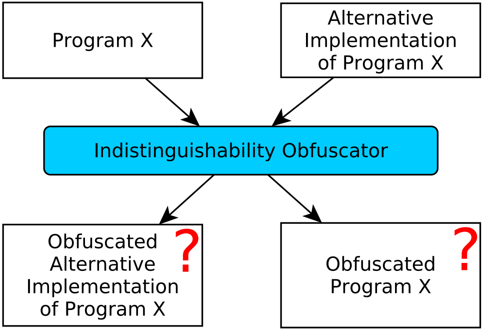

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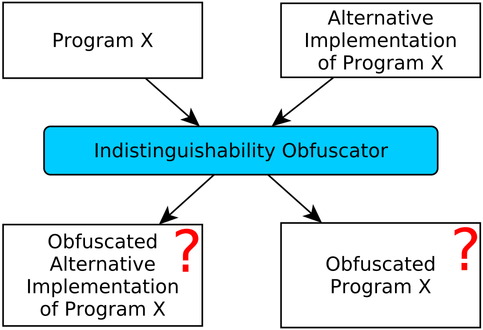

Cool stuff, but let's look at obfuscation we can use in practice.

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Categorization of Obfuscation

What types of obfuscation transformations exist?

- **Static Vs. Dynamic**
  - **Static obfuscation**:
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- **Point of insertion**:
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  - Machine code
- **Transformation targets**:
  - **Layout** → scramble identifiers and code layout
  - **Data** → obfuscate data (structures) embedded in code
  - **Control flow** → obfuscate secret algorithms

Outline

Compiler Optimizations

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- In-lining function bodies
- Loop unrolling
- Loop-invariant code motion
- Common sub-expression elimination
- Constant folding and propagation
- Dead code elimination
- Strength reduction
- more @ `http://en.wikipedia.org/wiki/Optimizing_compiler`

In-lining function bodies

Replace function call by function body

Before

```c
int foo(int a, int b) {
  return a + b;
}
...
c = foo(a, b+1);
```

After

```c
...
c = a + b + 1;
```

Loop unrolling

Remove "end-of-loop" test overhead

Before

```
...
for (i = 0; i < 2; i++)
{
  a[i] = 0;
}
```

After

```
...
a[0] = 0;
a[1] = 0;
```

Loop invariant code-motion

Extract operations whose results are independent of loop execution

Before

```
...
for (i = 0; i < 2; i++)
{
  a[i] = p + q;
}
```

After

```
...
temp = p + q;
for (i = 0; i < 2; i++)
{
  a[i] = temp;
}
```

Common subexpression elimination

Replace re-occurring identical (sub-)expressions by a single variable holding the result

Before

```
...
a = b + (z + 1);
p = q + (z + 1);
```

After

```
...
temp = z + 1;
a = b + temp;
p = q + temp;
```


Constant folding and propagation

Simplify constant expressions and substitute the values of known constants in expressions

Before

```
...
a = 3 + 5;
b = a + 1;
func(a, b);
```

After

```
...
func(8, 9);
```

Dead code elimination

Remove code which does not affect program results: unreachable code and code that affects variables that are irrelevant for the program

Before

```
...
a = 1;
if (a < 0)
{
  printf("This should never be printed!");
}
```

After

```
...
a = 1;
```


Strength reduction

Replace expensive operations with equivalent cheap ones

Before

```
...
y = x / 8;
p = q * 15;
```

After

```
...
y = x >> 3;
p = (q << 4) - x;
```


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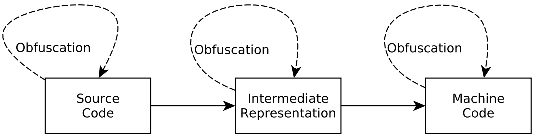
Automated Code Obfuscation



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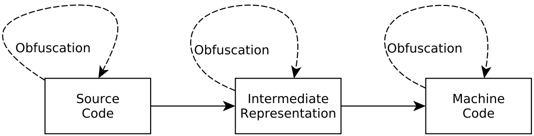

Obfuscation Techniques:

- Scramble identifiers
- Instruction substitution
- Garbage code insertion
- Merging and splitting functions
- Encode Literals
- Encode Arithmetic
- Opaque predicates
- Control-flow flattening
- Virtualization obfuscation
- White-box cryptography

Scramble identifiers

Replace identifier names with random strings

Before

```
...
sum = 0;
for (i = 0; i < arr_len; i++)
  sum += arr[i];
average /= arr_len;
```

After

```
...
za82b547bcb = 0;
for (z1c0ab7cf0c = 0; z1c0ab7cf0c < za862d19cbc;
     z1c0ab7cf0c++)
  za82b547bcb += zc1c28ca67f[z1c0ab7cf0c];
z8c8f7c7867 /= za862d19cbc
```

This layout obfuscation has high potency, but low resilience

Instruction substitution

Replace binary operation (e.g. +, -, AND, OR, XOR, etc.) by functionally equivalent, but more complicated computations

Before

```
...
a = b + c
```

After

```
...
r = rand();
a = b + r;
a = a + c;
a = a - r;
```

Garbage code insertion

Insert code that executes, but does not affect the IO behavior

Before

```
...
sum = 0;
for (i = 0; i < arr_len; i++)
  sum += arr[i];
average = sum / arr_len;
```

After

```
...
sum = 0; prod = 1;
for (i = 0; i < arr_len; i++) {
  sum += arr[i];
  prod *= arr[i];
}
average = sqrt(prod);
average = sum / arr_len;
```

Merging and splitting functions

- Merging implies combining the code of two or more functions into a single function
- Splitting implies dividing the code one function into two or more functions

Split

```
func1(int a, int b) {
  x = 4;
  if (a < 3)
    x = x + 6;
  x *= b;
}

func2(int a, int c) {
  y = a + 12;
  y = y/c;
}
```

Merged

```
func3(int a, int b, int c) {
  if (c % 2 == 0) {
    x = 4;
    if (a < 3)
      x = x + 6;
    x *= b;
  } else {
    y = a + 12;
    y = y/b;
  }
}
```

Encode Literals

- Literals are constant (hard-coded) strings and numeric values
- Literals can be encoded in numerous ways using encoder functions
- At runtime they are decoded back to their original value

Before

```c
main(int ac, char* av[]) {
  printf("hello\n");
  return 0;
}
```

After

```c
gen_str(char str[]) {
  int i = 0;
  str[i++] = 'h';
  str[i++] = 'e';
  str[i++] = 'l';
  str[i++] = 'l';
  str[i++] = 'o';
  str[i++] = '\n';
  str[i] = '\000';
}

main(int ac, char* av[]) {
  char str[7];
  gen_str(str);
  printf(str);
  return 0;
}
```

Encode Arithmetic (Mixed-Boolean Arithmetic)

- Replace arithmetic or Boolean expressions with more complex ones
- Complex expressions contain both arithmetic and boolean operators
- Transformation can be applied recursively to increase strength

Before

```
func(int x, int y) {
 return x + y;
}
```

After (Version 1)

```
func(int x, int y) {
 return 2*(x | y) - (x ^ y);
}
```

After (Version 2)

```
func(int x, int y) {
 return (x | y) + (x & y);
}
```


Opaque predicates and opaque expressions [6]

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An expression whose value is known to the defender (at obfuscation time), but which is difficult for an attacker to figure out statically.

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Notation:

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- P^F for an opaquely false predicate
- $P^?$ for an opaquely intermediate predicate (range divider)
- $E^{=v}$ for an opaque expression of value v

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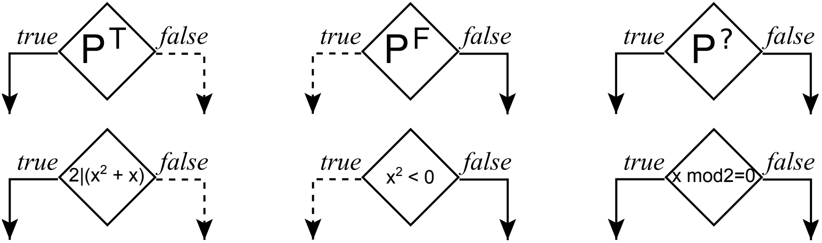
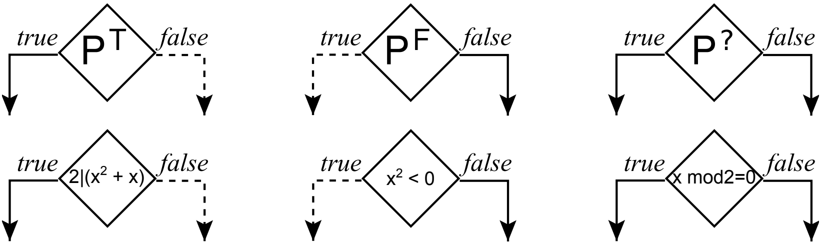


Bogus control-flow via opaque predicates

- Opaque predicates facilitate insertion of bogus control-flow:
  - Does not affect I/O behavior
  - Attacker does not know which code is bogus
  - Increases attack / analysis time
- Resilience of bogus control-flow reduced to resilience of opaque predicates



Bogus control-flow via opaque predicates

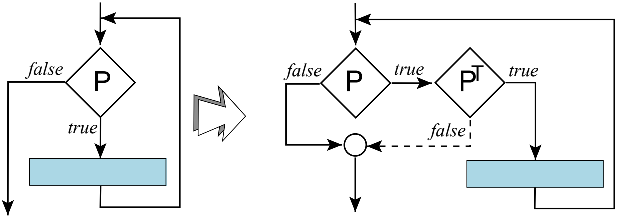
E.g. add an opaquely true predicate (P^T) to a *while* loop condition (P)

Before

```
i = 1;
while (i < 100) {
  dostuff(i);
  i++;
}
```

After

```
i = 1; j = 100;
while ((i < 100) &&
  (j*j*(j+1)*(j+1)%4 == 0)) {
  dostuff(i);
  i++;
  j = j*i+3;
}
```



Breaking opaque predicates via abstract interp.

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x is odd

```
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y = x * x; // odd
y = y + x; // even
if ( y % 2 == 0) // always
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else // dead branch
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x is even

```
x = ...; // any even number
y = x * x; // even
y = y + x; // even
if ( y % 2 == 0) // always
...              // true
else // dead branch
...
```

- Abstract interpretation is able to infer that regardless of x's value, the *IF* condition is always true

Opaquely intermediate predicate (Range divider)

- Range dividers can lead to different paths in the code
- No dead code
- All branches have the same behavior but different syntax

Before

```c
int main(int ac, char* av[]){
  char *str = av[1];
  int hash = 0;
  for(int i = 0;
      i < strlen(str);
      str++, i++) {
    hash = (hash<<7)^(*str);
  }
  if (hash == 809267)
    printf("You win!");
  return 0;
}
```

After

```c
int main(int ac, char* av[]){
  char *str = av[1];
  int hash = 0;
  for(int i = 0;
      i < strlen(str);
      str++, i++) {
    char chr = *str;
    if (chr > 42) {
      hash = (hash << 7) ^ chr;
    } else {
      hash = (hash * 128) ^ chr;
    }
  }
  if (hash == 809267)
    printf("You win!");
  return 0;
}
```

Control-flow flattening

- Remove the control-flow structure of functions:
  1. Put each basic block as a case inside a switch statement
  2. Wrap the switch inside an infinite loop

Control-flow flattening

- Remove the control-flow structure of functions:
  1. Put each basic block as a case inside a switch statement
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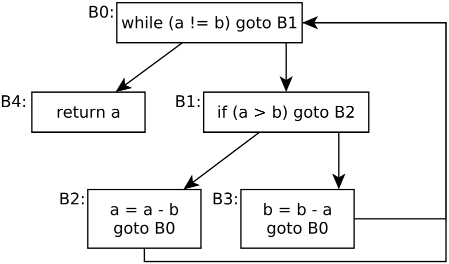
- Let's take one function, e.g. GCD

```c
int gcd(int a, int b){
  while (a != b)
    if (a > b)
      a = a - b;
    else
      b = b - a;
  return a;
}
```



Control-flow flattening GCD example

Before

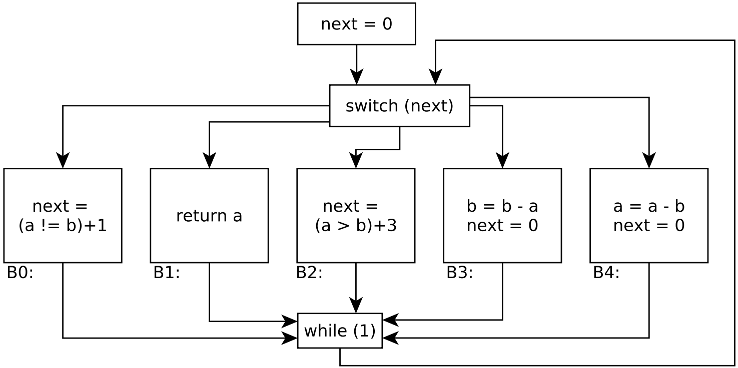
```
int gcd(int a, int b){
  while (a != b)
    if (a > b)
      a = a - b;
    else
      b = b - a;
  return a;
}
```

After

```
int gcd(int a, int b){
int next = 0;
while(1) {
  switch(next) {
    case 0:
      next = (int)(a != b) + 1;
      break;
    case 1: return a;
      break;
    case 2:
      next = (a > b) + 3;
      break;
    case 3: b = b - a;
      next = 0;
      break;
    case 4: a = a - b;
      next = 0;
      break;
    default:
      break;
}}}
```


Control-flow flattening GCD example

The CFG of the resulting code:



Control-flow flattening discussion

Performance penalty:

- For 3 SPEC programs: $4\times$ slowdown, $2\times$ size
- Reasons:
  - The wrapper loop condition check, plus jump
  - The switch `next` value check, plus indirect jump
- How to optimize:
  - Keep tight loops as one switch entry (don't split)
  - Use gcc's *labels-as-values* $\rightarrow$ allows jumping to next basic block

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Attack on control-flow flattening:

1. Find next block of every basic block
2. Rebuild original CFG

Mitigation: assign opaque expressions ($E^{=v}$) to `next`
Question: How do we build such opaque expressions?

Opaque expressions from array aliasing

1. A statically initialized **array with seemingly random values**:

   g =

10	5	13	3	27	5	24	38	0	73	115	3	66	60	17	31

2. The values are generated such that some **invariants** hold, e.g.:
   - Every 3rd cell starting from cell 0, contains a value $v \equiv 3 \mod 7$
   - Every 3rd cell starting from cell 1, contains a value $v \equiv 5 \mod 11$
   - Cells 2, 5, 8, 11 and 14 contain values 13, 5, 0, 3, respectively 17
3. **Update array cells** with values that respect invariants

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   - Cells 2, 5, 8, 11 and 14 contain values 13, 5, 0, 3, respectively 17
3. **Update array cells** with values that respect invariants

Let's replace right-hand values $0, 1, 2, 3$ and 4 of assignments to `next` with $E^{=0}, E^{=1}, E^{=2}, E^{=3}$, respectively $E^{=4}$:

- `next = 0` → `next = g[3] % g[11] - g[8]`
- `next = 1` → `next = 3 * g[11] - 4 * (g[4] % g[5])`
- `next = 2` → `next = g[5] - g[3]`
- `next = 3` → `next = g[2] % g[1]`
- `next = 4` → `next = g[15] - g[4]`

Next slide shows how this looks in the flattened GCD example

Control-flow flattening + opaque expressions

```
int gcd(int a, int b){
int g[] = {10, 5, 13, 3, 27, 5, 24, 38, 0, 73, 115,
     3, 66, 60, 17, 31};
int next = g[3] % g[11] - g[11]; // 0
while(1) {
  switch(next) {
    case 0:
      if(a != b)
        next = 3 * g[11] - 4 * (g[4] % g[5]); // 1
      else next = g[5] - g[3]; // 2
      break;
    case 1:
      if (a > b) next = g[2] % g[1]; // 3
      else next = g[15] - g[4]; // 4
      break;
    case 2: return a;
      break;
    case 3: a = a - b;
      next = g[3] % g[11] - g[8]; // 0
      break;
    case 4: b = b - a;
      next = g[3] % g[11] - g[8]; // 0
      break;
    default:
      break;
}}}
```

Opaque expressions from pointer aliasing

Assumption: pointer aliasing is a computationally hard static analysis problem

1. Construct one or more linked-lists
2. Set pointers into those linked-lists
3. Create opaque predicates by checking properties you know to be true / false, e.g.:
   - → q_1 points to a node with value $v > 53$
   - → q_2 points to a node with value $v \leq 53$

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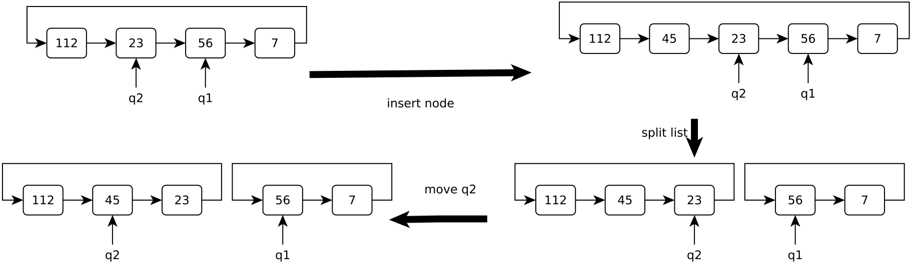
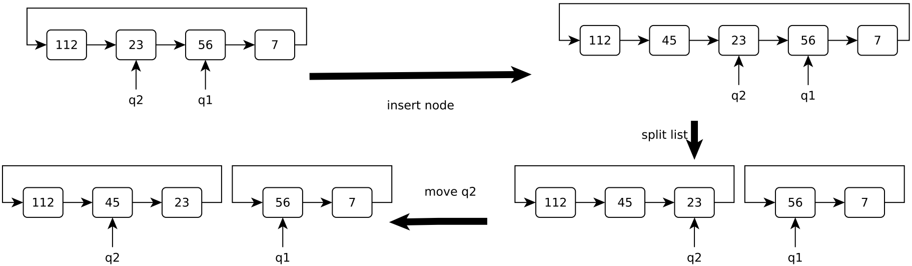


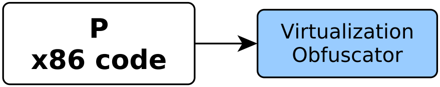
Opaque expressions from pointer aliasing



- One opaquely true predicate: $(*q_1 > *q_2)^T$
- After performing several operations to confuse alias analysis another opaque predicate is: $(q_1 \neq q_2)^T$

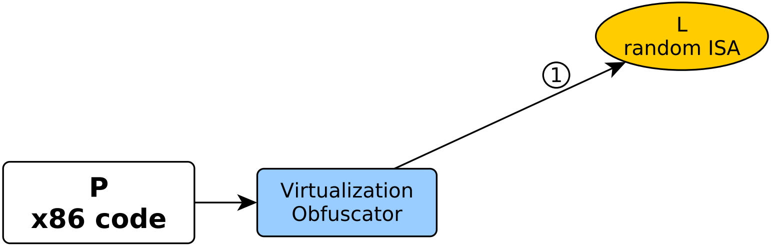
Virtualization Obfuscation

- **Goal:** Hide secret **algorithm** of program P



Virtualization Obfuscation

- **Goal:** Hide secret **algorithm** of program P
- **Obfuscation Procedure:**
  1. Generate random bytecode ISA (L) covering all instructions of P



Virtualization Obfuscation

- **Goal:** Hide secret **algorithm** of program *P*
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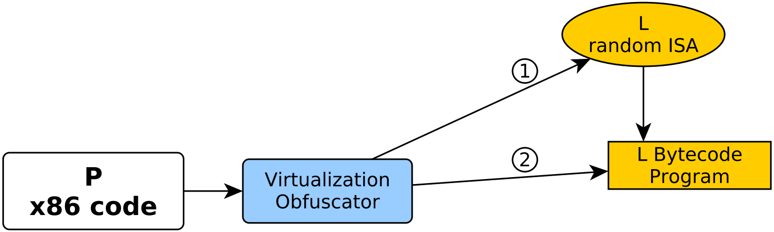
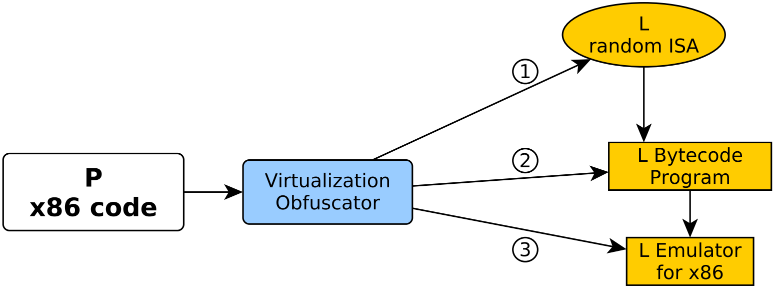
  2. Translate *P* to *L* bytecode program



Virtualization Obfuscation

- **Goal:** Hide secret **algorithm** of program P
- **Obfuscation Procedure:**
  1. Generate random bytecode ISA (L) covering all instructions of P
  2. Translate P to L bytecode program
  3. Generate emulator to interpret L bytecode on x86 machine



Virtualization Obfuscation

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- **Obfuscation Procedure:**
  1. Generate random bytecode ISA (L) covering all instructions of P
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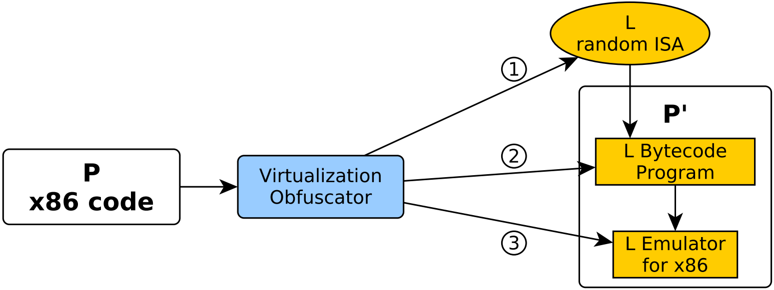
- Obfuscated program (P') consists of bytecode program and emulator



Virtualization Obfuscation Example [11]

We apply virtualization obfuscation to function `foo`, written in C

```c
1 void foo(int x){
2   int y = 10;
3   y++;
4   y++;
5   if (x > 0){
6       y++;
7   }
8   else {}
9   printf("%d\n",y);
10 }
```

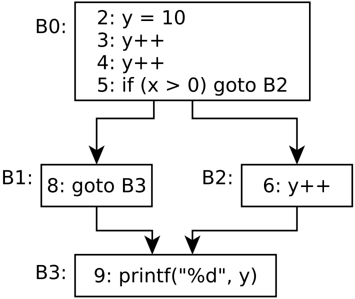


Figure : CFG of `foo`

Virtualization Obfuscation Example

Step 1: Generate random bytecode ISA covering all instructions of `foo`

```
1  void foo(int x){
2    int y = 10;
3    y++;
4    y++;
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7    }
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```

Random ISA:

1. Integer assignment (line 2)
   $\xrightarrow{\textit{encode}}$ 52, LH_op, RH_op

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   $\xrightarrow{encode}$ 03, op

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   $\xrightarrow{\textit{encode}}$ 08, tst_op, jmp_offset

Virtualization Obfuscation Example

Step 1: Generate random bytecode ISA covering all instructions of `foo`

```
1  void foo(int x){
2    int y = 10;
3    y++;
4    y++;
5    if (x > 0){
6       y++;
7    }
8    else {}
9    printf("%d\n",y);
10 }
```

Random ISA:

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   $\xrightarrow{\textit{encode}}$ 08, tst_op, jmp_offset
4. Call to `printf` (line 9)
   $\xrightarrow{\textit{encode}}$ 18, op

Virtualization Obfuscation Example

Variables and constants of bytecode program stored in array: `data`

- `data[0]` represents variable `x`
- `data[1]` represents variable `y`
- `data[2]` represents constant for initialization to 10 (line 2 of `foo`)
- `data[3]` represents constant jump offset of conditional branch

```
1  void foo(int x){
2    int y = 10;
3    y++;
4    y++;
5    if (x > 0){
6        y++;
7    }
8    else {}
9    printf("%d\n",y);
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```

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   $\xrightarrow{\textit{encode}}$ 18, op

Virtualization Obfuscation Example

Step 2: Translate `foo` to bytecode program

- `data = {00,00,10,05} // {x, y, init_const, jmp_offset}`
- Bytecode: {52, 01, 02, 03, 01, 03, 01, 08, 00, 03, 03, 01, 18, 01, 00}

```
1  void foo(int x){// bytecode
2    int y = 10; // 52, 01, 02
3    y++;        // 03, 01
4    y++;        // 03, 01
5    if (x > 0){ // 08, 00, 03
6        y++;    // 03, 01
7    }
8    else {}
9    printf("%d",y); // 18, 01
10 }                 // 00
```

Random ISA:

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Virtualization Obfuscation Example

Step 3: Generate emulator to interpret bytecode on x86 machine

```
int data = {00,00,10,05};
{x, y, init_const, jmp_off}

int code = {
52, 01, 02,
03, 01,
03, 01,
08, 00, 03,
03, 01,
18, 01,
00};
```

Virtualization Obfuscation Example

Step 3: Generate emulator to interpret bytecode on x86 machine

```
int data = {00,00,10,05};
{x, y, init_const, jmp_off}

int code = {
52, 01, 02,
03, 01,
03, 01,
08, 00, 03,
03, 01,
18, 01,
00};
```

```
int vpc = 0, op1, op2;
while (true) {
  switch(code[vpc]) {
    case 03: // increment
      op1 = code[vpc + 1];
      data[op1]++;
      vpc += 2; break;
    case 08: // conditional jump
      op1 = code[vpc + 1];
      op2 = code[vpc + 2];
      if (data[op1] > 0)
        vpc += 3;
      else
        vpc += data[op2];
      break;
    case 18: // call printf
      op1 = code[vpc + 1];
      printf("%d\n", data[op1]);
      vpc += 2; break;
    case 52: // assignment
      op1 = code[vpc + 1];
      op2 = code[vpc + 2];
      data[op1] = data[op2];
      vpc += 3; break;
    default: return; // halt
  } // end switch
} // end while
```


Virtualization Obfuscation Example

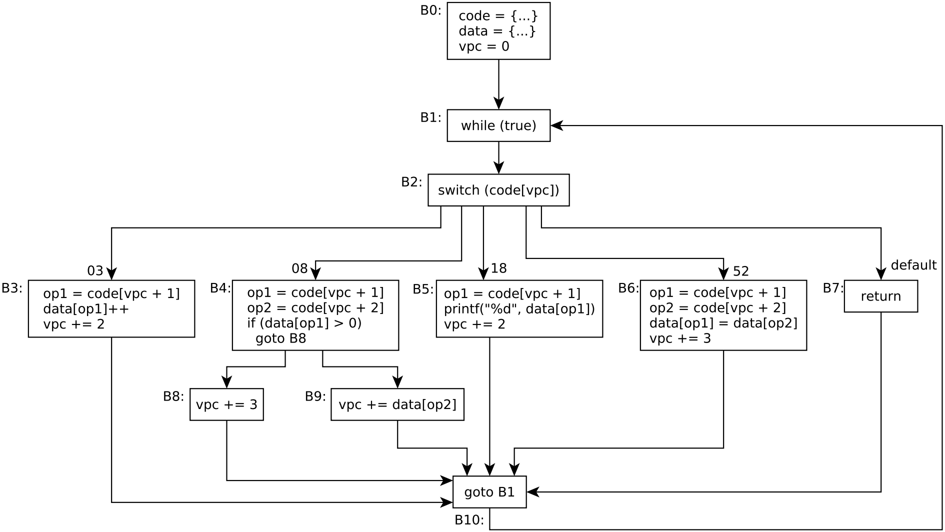

Figure : Control flow graph of obfuscated `foo`

Virtualization Obfuscation

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  - Many other obfuscation techniques can be added on top of:
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  - Many other obfuscation techniques can be added on top of:
    - Each `case` branch
    - The `switch` statement
    - The `data` and `code` arrays
- **Tools:**
  - CodeVirtualizer (59 € - 119 €)
  - VMProtect (69 € - 599 €)
  - Tigress, Diablo (Free research tools)

White-Box Cryptography (WBC)

- **Idea:**
  - Embed the key inside the cipher (e.g. in S-boxes)
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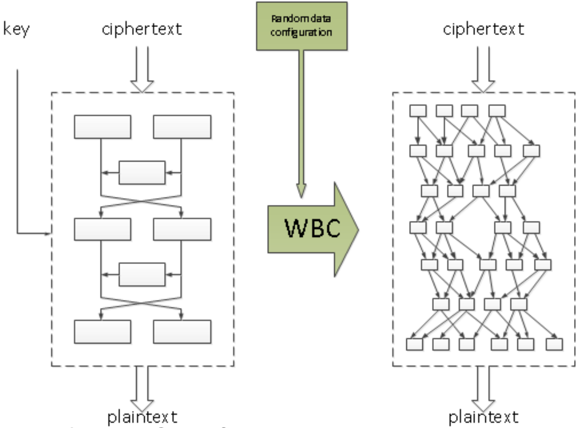
Source: `http://www.whiteboxcrypto.com/`



White-Box Cryptography (WBC)

- **Idea:**
  - Embed the key inside the cipher (e.g. in S-boxes)
  - Convert cipher computation into large network of look-up tables
- **Attack:** WB-AES and WB-DES broken (2^{22} operations)

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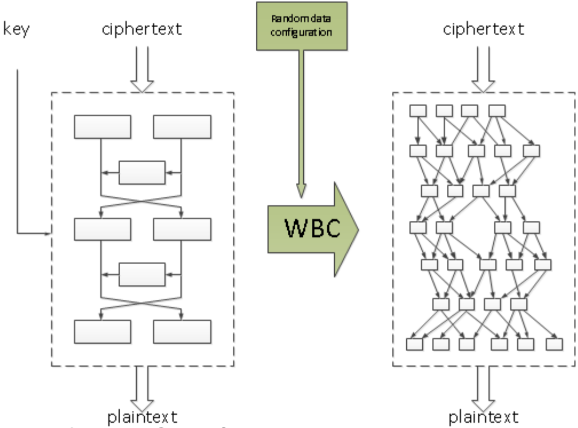

Some Details on WBC

Before

```c
char xor(char inputs)
{
  char a = inputs & 0x0F;
  char b = inputs >> 4;
  return a ^ b;
}
```

After

```c
char lut[256] =
{
  0x00, 0x01, 0x02, ..., 0x0F,
  0x01, 0x00, 0x03, ..., 0x0E,
  0x02, 0x03, 0x00, ..., 0x0D,
   |                      |
  0x0F, 0x0E, 0x0D, ..., 0x00
};

char xor(char inputs)
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}
```

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   |                      |
  0x0F, 0x0E, 0x0D, ..., 0x00
};

char xor(char inputs)
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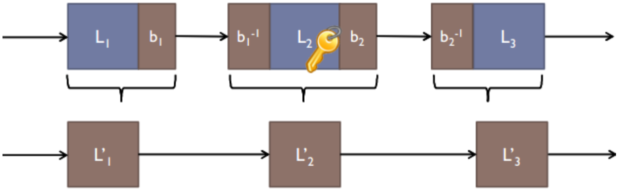
```

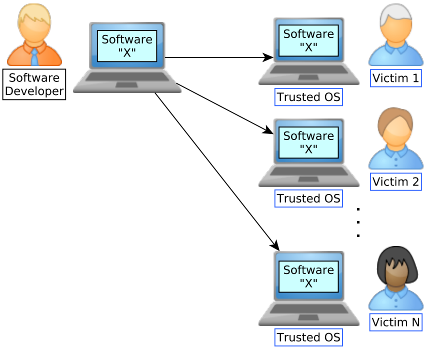


Source: PhD presentation of B. Wyseur

Outline

Software Diversity

1. Software developer distributes software X to all end-users



Software Diversity

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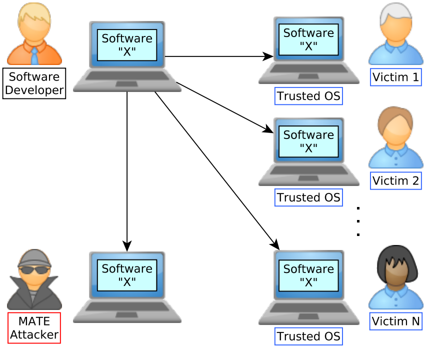

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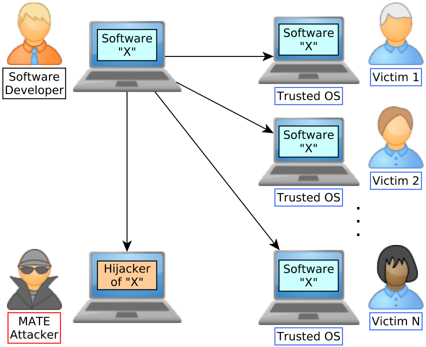

Software Diversity

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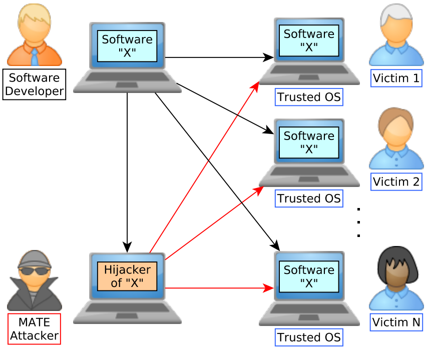
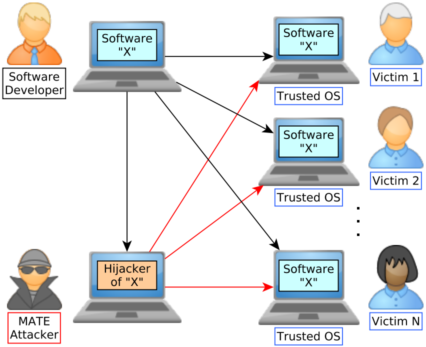
3. MATE reverse engineers X and builds a hijacker of X
4. MATE distributes hijacker to other end-users of X



Software Diversity

- What can we do to protect victims?



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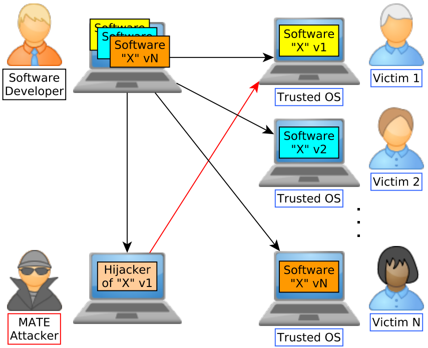

Software Diversity

- What can we do to protect victims?
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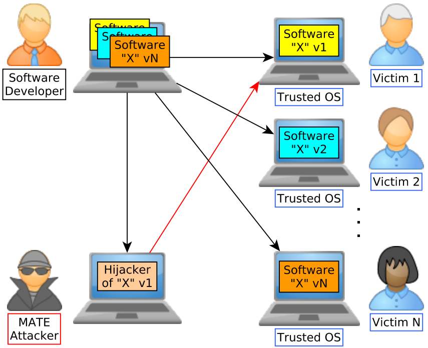
- Generate 1000s of different versions using obfuscation



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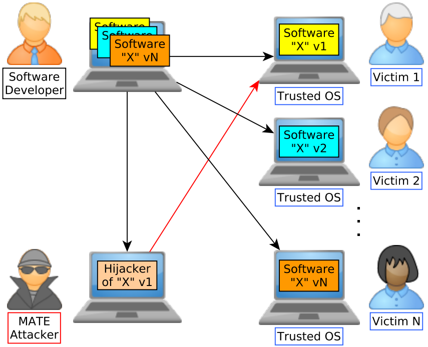

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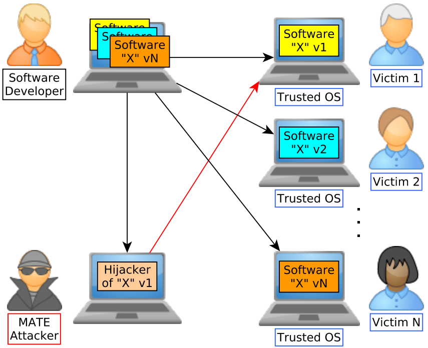

Pre- vs. Post-Distribution Software Diversity

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Post-Distribution Software Diversity

- Software developer embeds self-modifying code in application
- All end-users may get the same binary from software developer
- Code may change differently for different users depending on inputs
- Next we present dynamic obfuscation techniques which can be used for post-distribution diversification

Outline

1 Introduction

2 Obfuscation in Theory

3 Obfuscation in Practice
- Static Obfuscation
  - Compiler Optimizations
  - Automated Code Obfuscation
- Software Diversity
- Dynamic Obfuscation

4 The Strength of Obfuscation

5 Hands-on Tutorial

6 Conclusions

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- A dynamic obfuscator runs in two phases:
  1. At **compile-time**:
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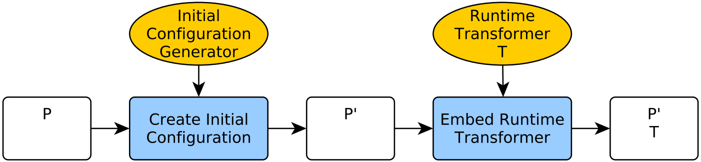

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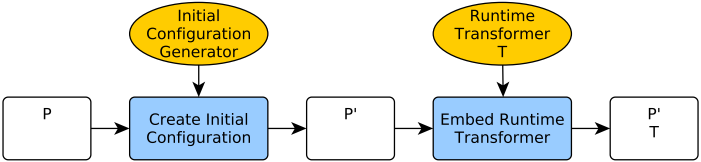
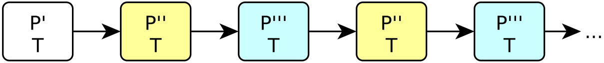


  2. At **runtime**:
     - Interleave execution of the program with calls to the transformer T
     - T changes the code segment content at runtime
     - Ideally a non-repeating series of configurations, **in practice** they repeat



Dynamic Obfuscation Techniques

General Techniques:

- **Build-and-execute**: generate code for a routine at runtime, and jump to it
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The **attacker's goals** can be to:

- Recover the original code
- Modify the original code

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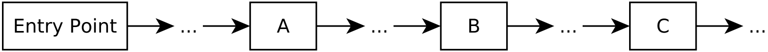
- **Implementation** by choosing 3 points A, B and C in the CFG:
  1. All paths to B must flow through A and all paths from B must flow through C
  2. A replaces bogus instruction at B with real instruction
  3. C replaces real instruction at B with bogus instruction



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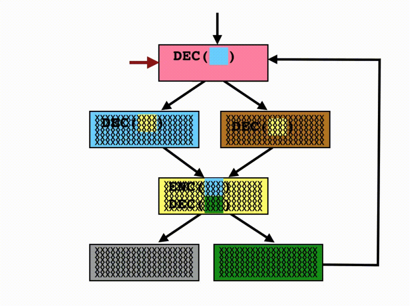

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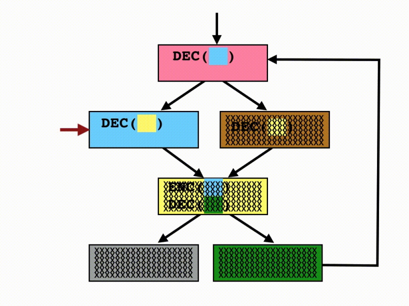

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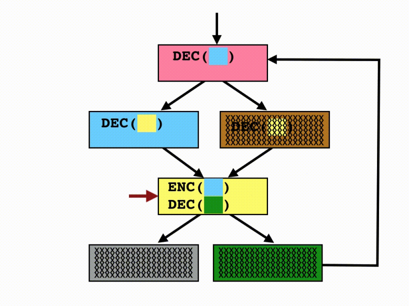

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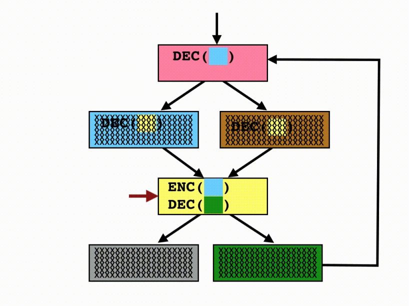

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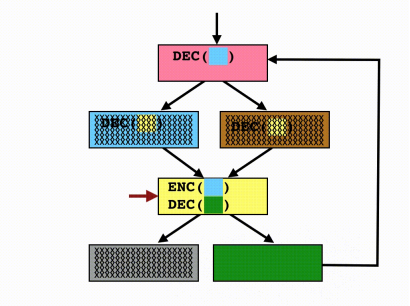

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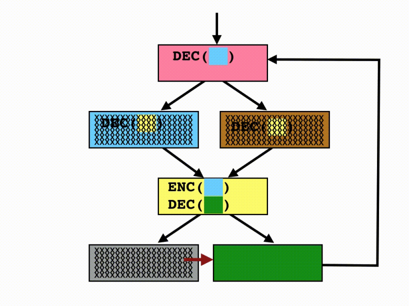

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  - Time overhead added to program execution after obfuscation
  - Size of the obfuscated binary relative to original binary

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  - Attacker develops automated crack based on symbolic execution
    - $\rightarrow$ **resilience** $>$ 50 USD $\times$ Nr. of users not willing to pay

Symbolic Execution in a Nutshell

- Interpret program using symbolic values instead of concrete ones

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int main(int ac, char* av[]) {
  int a = atoi(av[1]);
  int b = atoi(av[2]);
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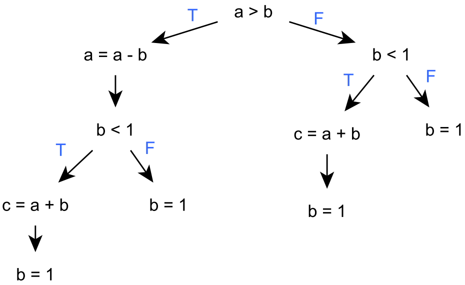

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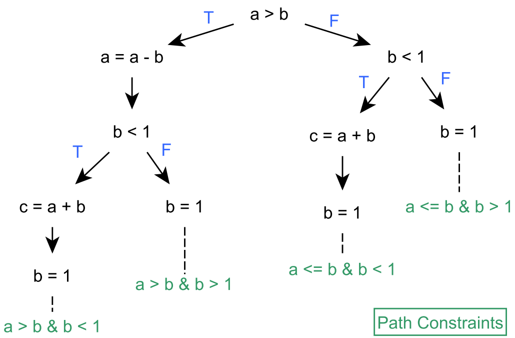

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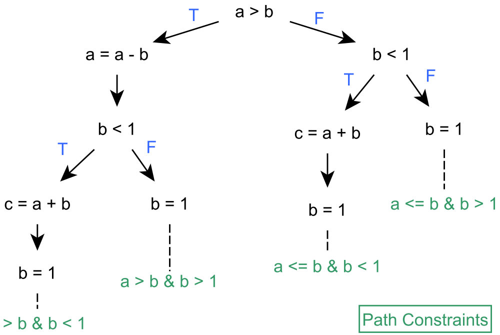
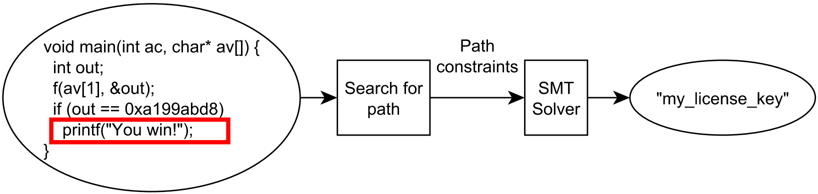


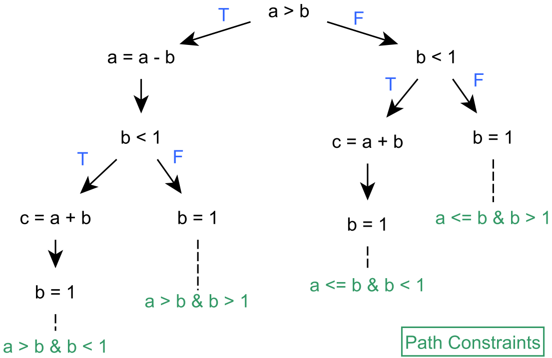
Bypassing License Checks via Symbolic Execution

1. Make license input symbolic
2. Indicate distinct statement executed when license key is correct
3. Explore paths until desired instruction (sequence) is found
4. Solve path constraints on paths that lead to desired instruction via SMT solver
5. Find satisfiable path constraints → concrete inputs to bypass check



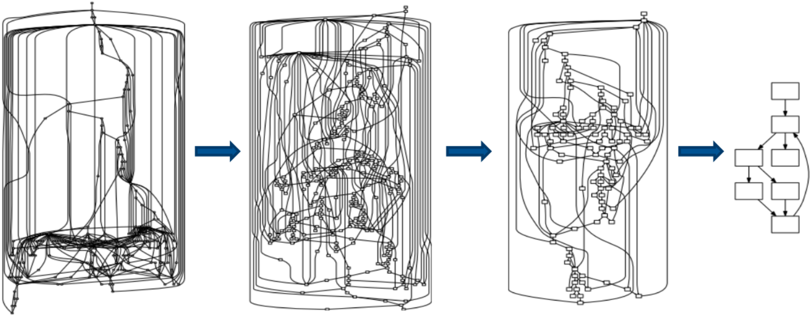
Are other Attacks Possible via Symbolic Execution?

- Yes! Symbolic execution is a prerequisite for several attacks:
  - Simplify control-flow graph
  - Identify & disable tamper-proofing checks
  - Bypass authentication checks / trigger conditions



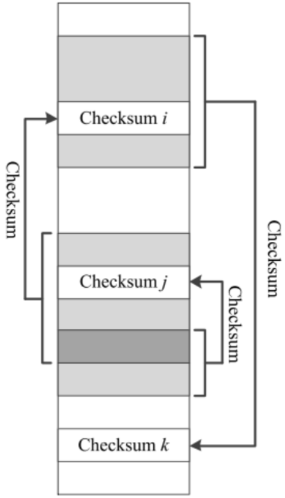
Simplifying the CFG (Yadegari et al. [14])

1. Explore paths such that all code is covered
2. Simplify traces using compiler optimization tricks
3. Reconstruct CFG from traces



Identify & Disable Checks (Qiu et al. [13])

1. Taint code segment
2. Explore paths until enough self-checks disabled (cyclic checks → explore all code)
3. Disable self-checking instructions



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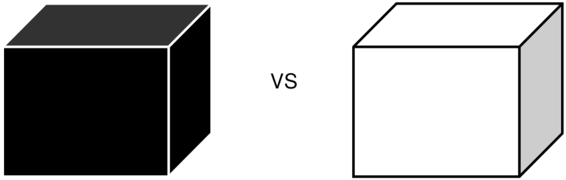
- Generate test cases:
  - **Black-box test generation:** Fuzzing, Random testing
  - **White-box test generation:** Symbolic/Concolic execution



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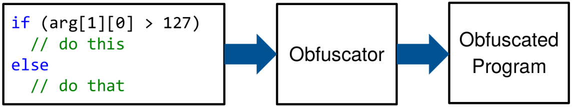

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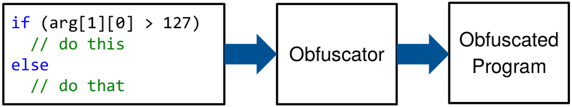
  $\rightarrow$ No increase in black-box test case generation time
- **Example:**



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Measuring Obfuscation Strength

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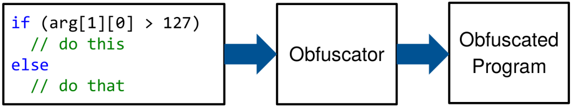

- **Observation:** Could be faster to use black-box test generator than white-box
- **Conclusion:** Apply obfuscation transformations until white-box slower than black-box test case generation

Code Tampering Attacks

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- **Answer:**
  - Test case generation is non-invasive attack, i.e. code is read, not changed
  - Obfuscation aims to defend against MATE attacker (can tamper with code)
  - Easy to find and patch-out crypto hash functions

Metrics for Measuring Obfuscation Strength

- Number of lines of code
- McCabe cyclomatic complexity
- Nesting complexity
- Data flow complexity
- Object oriented design metrics
- Data structure complexity
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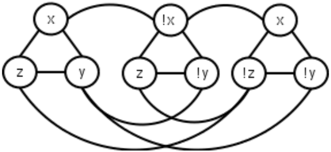
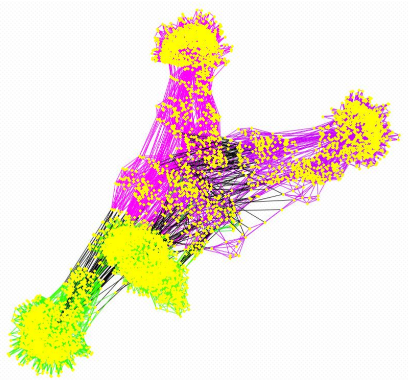
- SAT metrics: Graph metrics on a SAT formula represented as a graph

  $(x+y+z)\cdot(!x+!y+z)\cdot(x+!y+!z)$



SAT Instance Before & After Obfuscation

Figure : Before Obfuscation (7.5 sec)



```c
unsigned int SDBMHash(char* str, unsigned int len)
{
   unsigned int hash = 0;
   unsigned int i    = 0;
   for(i = 0; i < len; str++, i++)
      hash = (*str) + (hash << 6)
             + (hash << 16) - hash;
   return hash;
}

int main(int argc, char* argv[]) {
  unsigned char *str = argv[1];
  unsigned int hash = SDBMHash(str, strlen(str));

  if (hash == 0x89dcd66e)
    printf("You win!\n");
  return 0;
}
```

SAT Instance Before & After Obfuscation

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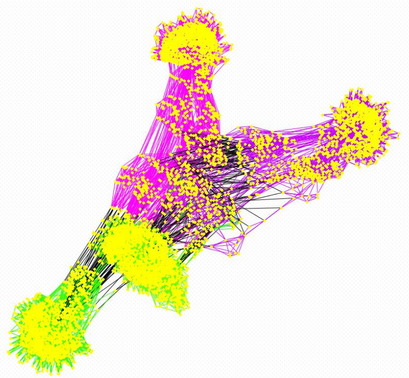
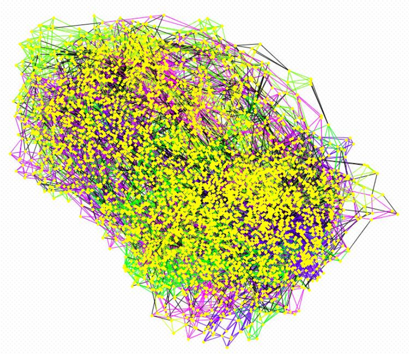


Figure : After Obfuscation (438 sec)



Strong obfuscation transformations destroy community structures

Outline

Hands-on Tutorial Overview

Example of bypassing password check in C programs

1. Start with plain unobfuscated program (break with static analysis)
2. Discuss the option of using hash functions (break with patching)
3. Add one obfuscation layer (break with symbolic execution)
4. Add more obfuscation layers (harder to break)

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- Tools we are going to use:
  - We assume you have Docker installed and have basic user knowledge
  - Docker image based on Ubuntu contains: Tigress, KLEE, STP, Z3, SatGraf, etc.

    ```
    $ docker pull banescusebi/obfuscation-symex
    $ docker run -it banescusebi/obfuscation-symex
    ```
  - For instructions on how to start the Docker image read description at `https://hub.docker.com/r/banescusebi/obfuscation-symex/`
  - Instructions for running GUI apps available for Ubuntu and Mac OS (not mandatory, only needed for SatGraf)

Bypassing Password Check in Unobfuscated Program

Example C Program with Hard-Coded Password

```c
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int main(int argc, char* argv[]) {
  if (strcmp(argv[1],
      "my_license_key") == 0)
    printf("You win!\n");
  return 0;
}
```

- Hard-coded password can be found via static analysis

```
$ ./nohash my_license_key
You win!
$ strings nohash | grep ''license''
my_license_key
```

Bypassing Password Check even when Using Hash

Example C Program where Hard-Coded Password Replaced with Hash

```c
unsigned int BPHash(char* str, unsigned int len)
{
  unsigned int hash = 0;
  unsigned int i    = 0;
  for(i = 0; i < len; str++, i++) {
    hash = hash << 7 ^ (*str);
  }
  return hash;
}

int main(int argc, char* argv[]) {
  unsigned char *str = argv[1];
  unsigned int hash = BPHash(str, strlen(str));
  if (hash == 0x5bfaf2f9)
    printf("You win!\n");
  return 0;
}
```

- Check can still be disabled using binary patching

$ `strings bphash | grep ''license''`

$ `objdump -D bphash`

- Use vi in hex editor mode (`:%!xxd`) to patch check (`jne`)

Bypassing Password Check after Obfuscation

- **Add one layer of obfuscation:**

```
$ tigress --Transform=EncodeArithmetic
  --Functions=DEKHash --out=dekhash-obf/dekhash-encA.c
  dekhash.c
$ tigress --Transform=Flatten --Functions=DEKHash
  --out=dekhash-obf/dekhash-flat.c dekhash.c
$ tigress --Transform=Virtualize --Functions=DEKHash
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- **Apply symbolic execution** to each of these programs (see KLEE command on next slide)

```
$ ~/scripts/step05-klee-symex-until-win.sh . exe 15
```

The KLEE Symbolic Execution Tool

```
klee --optimize
  // Optimize before execution
  --emit-all-errors
  // Don't stop on first error
  --libc=uclibc
  // Choose libc version
  --posix-runtime
  // Link with POSIX runtime
  --only-output-states-covering-new
  // Only tests covering new code
  --max-time=3600
  // Halt after given nr. of sec.
  --write-smt2s
  // Write smt2 file per test
  --output-dir=klee-out-${file_name}
  // Output directory for tests
  ./${file_name}.bc
  // Bitcode file under test
  --sym-arg 5
  // Length of symbolic arg.
```

Viewing Results

- **See number of nanoseconds needed for KLEE to analyze a bitcode program**

```
$ cat klee-time-to-win.txt
```

- **Check differences between 1 and 2 layers of obfuscation**

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- **See number of nanoseconds needed for KLEE to analyze a bitcode program**

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- **Check differences between 1 and 2 layers of obfuscation**
- **Convert the SMT2 instances generated by KLEE into CNF instances**

$ `~/scripts/step07-convert-smt-to-cnf.sh . obfuscated-cnf-instances.txt`

$ `ll ./obfuscated-cnf-instances`

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$ `ll ./obfuscated-cnf-instances`

- **View CNF instances in SatGraf:**

$ `java -jar ~/satgraf/dist/SatGraf.jar com -f obfuscated-cnf-instances/dekhash-virt.cnf`

- **Check differences between 1 and 2 layers of obfuscation**

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- Multiple transformations should be combined to improve strength

Thank you for your attention

Questions ?

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