CSc 466/566

Computer Security

7 : Man-At-The-End — Obfuscation I

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Overview

Code obfuscation — what is it?

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- "Hard?" $\Rightarrow$ Harder than before!

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- static obfuscation $\Rightarrow$ obfuscated programs that remain fixed at runtime.
  - tries to thwart static analysis
  - attacked by dynamic techniques (debugging, emulation, tracing).

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- static obfuscation $\Rightarrow$ obfuscated programs that remain fixed at runtime.
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  - attacked by dynamic techniques (debugging, emulation, tracing).
- dynamic obfuscators $\Rightarrow$ transform programs continuously at runtime, keeping them in constant flux.
  - tries to thwart dynamic analysis

Bogus Control Flow

Complicating control flow

- Transformations that make it difficult for an adversary to analyze the flow-of-control:
  1. insert bogus control-flow

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- Transformations that make it difficult for an adversary to analyze the flow-of-control:
  1. insert bogus control-flow
  2. flatten the program
  3. hide the targets of branches to make it difficult for the adversary to build control-flow graphs
- None of these transformations are immune to attacks

Opaque Expressions

- Simply put:

  an expression whose value is known to you as the defender (at obfuscation time) but which is difficult for an attacker to figure out

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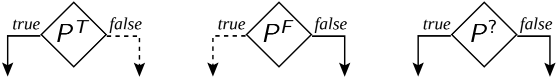
- Notation:
  - P^T for an *opaquely true* predicate
  - P^F for an *opaquely false* predicate
  - $P^?$ for an *opaquely indeterminate* predicate
  - $E^{=v}$ for an *opaque* expression of value v

Opaque Expressions

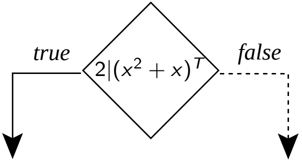
- Graphical notation:



- Building blocks for many obfuscations.

Opaque Expressions

- An opaquely true predicate:



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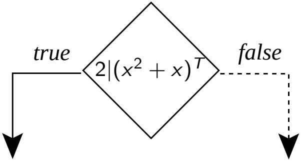

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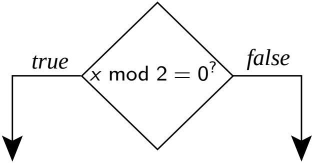

Inserting bogus control-flow

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  1. dead branches which will never be taken

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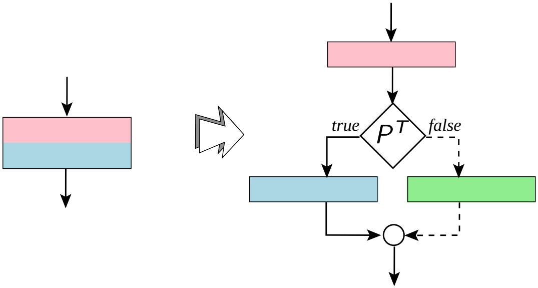
  1. dead branches which will never be taken
  2. superfluous branches which will *always* be taken
  3. branches which will sometimes be taken and sometimes not, but where this doesn't matter
- The resilience reduces to the resilience of the opaque predicates.

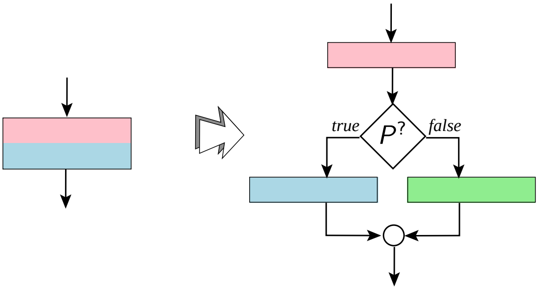
Inserting bogus control-flow

- A bogus block (green) appears as it might be executed while, in fact, it never will:



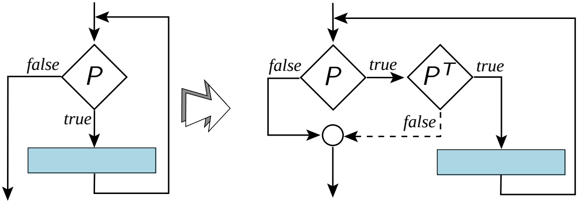
Inserting bogus control-flow

- Sometimes execute the blue block, sometimes the green block.
- The green and blue blocks should be semantically equivalent.



Inserting bogus control-flow

- Extend a loop condition P by conjoining it with an opaquely true predicate P^T:



Control Flow Flattening

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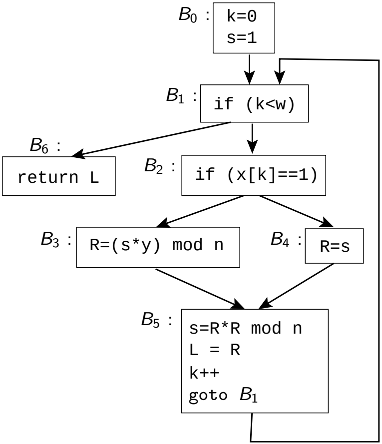
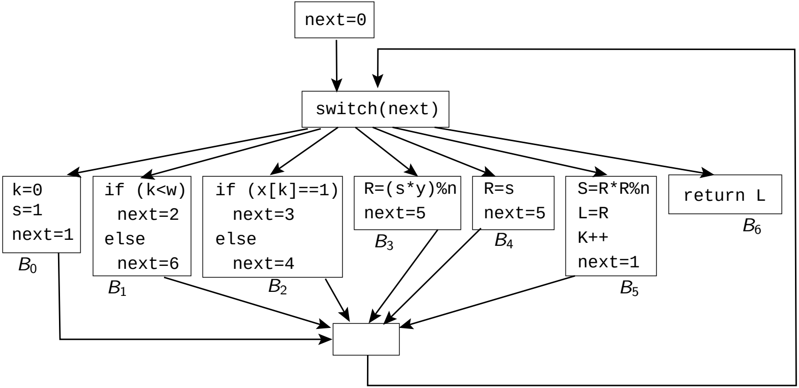
- Chenxi Wang's PhD thesis:

```
int modexp(int y, int x[],
           int w, int n) {
    int R, L;
    int k = 0;
    int s = 1;
    while (k < w) {
        if (x[k] == 1)
            R = (s*y) % n;
        else
            R = s;
        s = R*R % n;
        L = R;
        k++;
    }
    return L;
}
```



```
int modexp(int y, int x[], int w, int n) {
    int R, L, k, s;
    int next=0;
    for(;;)
        switch(next) {
            case 0 : k=0; s=1; next=1; break;
            case 1 : if (k<w) next=2; else next=6; bre
            case 2 : if (x[k]==1) next=3; else next=4;
            case 3 : R=(s*y)%n; next=5; break;
            case 4 : R=s; next=5; break;
            case 5 : s=R*R%n; L=R; k++; next=1; break;
            case 6 : return L;
        }
}
```



next=0
switch(next)
k=0
s=1
next=1
B0
if (k<w)
next=2
else
next=6
B1
if (x[k]==1)
next=3
else
next=4
B2
R=(s*y)%n
next=5
B3
R=s
next=5
B4
S=R*R%n
L=R
K++
next=1
B5
return L
B6

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  2. the switch incurs a bounds check the `next` variable,
  3. the switch incurs an indirect jump through a jump table.
- Optimize?
  1. Keep tight loops as one switch entry.
  2. Use `gcc`'s labels-as-values $\Rightarrow$ a jump table lets you jump directly to the next basic block.

Attack against Control-flow flattening

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  1. Work out what the next block of every block is.

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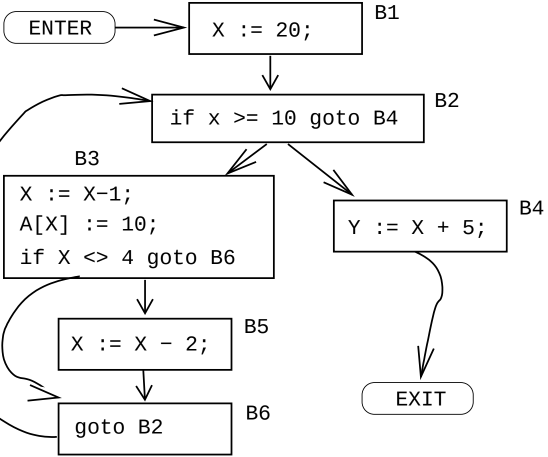
  1. Work out what the next block of every block is.
  2. Rebuild the original CFG!
- How does an attacker do this?
  1. use-def data-flow analysis
  2. constant-propagation data-flow analysis

next as an opaque predicate!

```
int modexp(int y, int x[], int w, int n) {
   int R, L, k, s;
   int next=E^{=0};
   for(;;)
      switch(next) {
         case 0 : k=0; s=1; next=E^{=1}; break;
         case 1 : if (k<w) next=E^{=2}; else next=E^{=6}; break;
         case 2 : if (x[k]==1) next=E^{=3}; else next=E^{=4};
                  break;
         case 3 : R=(s*y)%n; next=E^{=5}; break;
         case 4 : R=s; next=E^{=5}; break;
         case 5 : s=R*R%n; L=R; k++; next=E^{=1}; break;
         case 6 : return L;
      }
}
```

In-Class Exercise

1. Flatten this CFG:



2. Give the source code for the flattened graph above.

Constructing Opaque Predicates

Opaque values from array aliasing

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
36	58	1	46	23	5	16	65	2	41	2	7	1	37	0	11	16	2

Invariants:

1. every third cell (in pink), starting will cell 0, is $\equiv 1 \bmod 5$;
2. cells 2 and 5 (green) hold the values 1 and 5, respectively;
3. every third cell (in blue), starting will cell 1, is $\equiv 2 \bmod 7$;
4. cells 8 and 11 (yellow) hold the values 2 and 7, respectively.

Opaque values from array aliasing

- You can update a pink element as often as you want, with any value you want, as long as you ensure that the value is always $\equiv 1 \bmod 5$!
- That is, make any changes you want, while maintaining the invariant.
- This will make static analysis harder for the attacker.

```c
int g[] = {36,58,1,46,23,5,16,65,2,41,
           2,7,1,37,0,11,16,2,21,16};

if ((g[3] % g[5])==g[2])
    printf("true!\n");

g[5] = (g[1]*g[4])%g[11] + g[6]%g[5];
g[14] = rand();
g[4] = rand()*g[11]+g[8];

int six = (g[4] + g[7] + g[10])%g[11];
int seven = six + g[3]%g[5];
int fortytwo = six * seven;
```

- pink: opaquely true predicate.
- blue: g is constantly changing at runtime.
- green: an opaque value 42.

Initialize g at runtime!

```
int modexp(int y, int x[], int w, int n) {
   int R, L, k, s;
   int next=0;
   int g[] = {10,9,2,5,3};
   for(;;)
      switch(next) {
         case 0 : k=0; s=1; next=g[0]%g[1]^{=1}; break;
         case 1 : if (k<w) next=g[g[2]]^{=2};
                  else next=g[0]-2*g[2]^{=6}; break;
         case 2 : if (x[k]==1) next=g[3]-g[2]^{=3};
                  else next=2*g[2]^{=4}; break;
         case 3 : R=(s*y)%n; next=g[4]+g[2]^{=5}; break;
         case 4 : R=s; next=g[0]-g[3]^{=5}; break;
         case 5 : s=R*R%n; L=R; k++; next=g[g[4]]%g[2]^{=1};
                  break;
         case 6 : return L;
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```

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- Create an obfuscating transformation from a known computationally hard static analysis problem.

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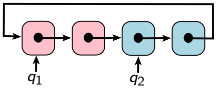
- Of course, these assumptions may be false!

- Construct one or more heap-based graphs, keep pointers into those graphs, create opaque predicates by checking properties you know to be true.



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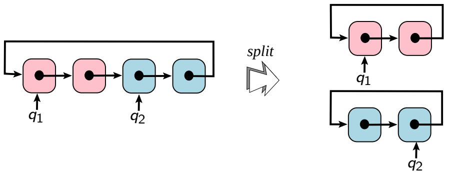
- q_1 and q_2 point into two graphs G_1 (pink) and G_2 (blue):



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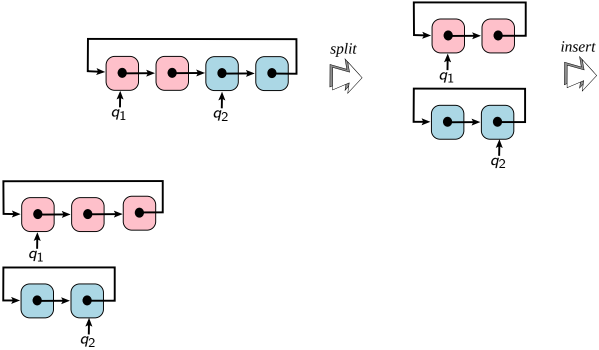

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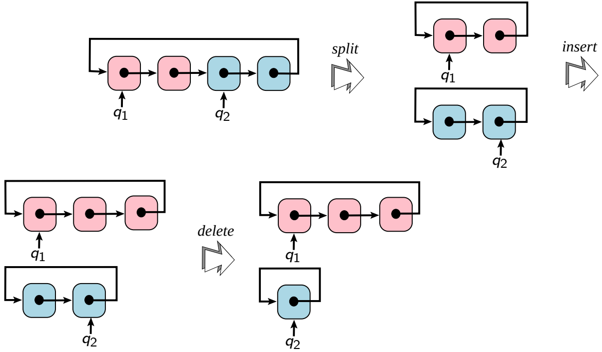

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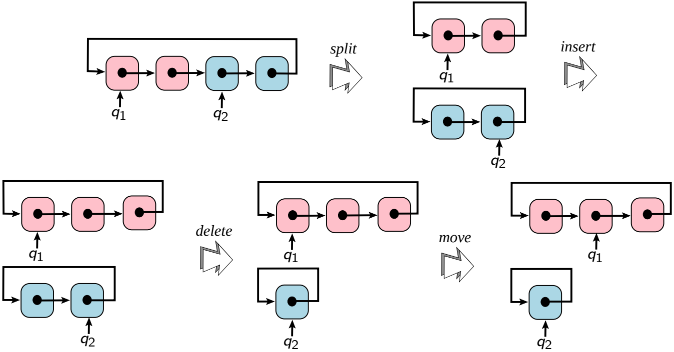

Invariants

- Two invariants:
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Invariants

- Two invariants:
  - "G_1 and G_2 are circular linked lists"
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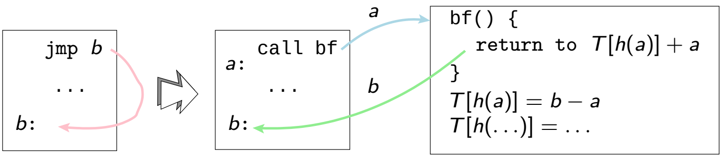
- Perform enough operations to confuse even the most precise alias analysis algorithm,
- Insert opaque queries such as $(q_1 \neq q_2)^T$ into the code.

Branch Functions

Jumps through branch functions

- Replace unconditional jumps with a call to a branch function.
- Calls normally return to where they came from... But, a branch function returns to the target of the jump!



Jumps through branch functions

- Designed to confuse disassembly.
- 39% of instructions are incorrectly assembled using a linear sweep disassembly.
- 25% for recursive disassembly.
- Execution penalty: 13%
- Increase in text segment size: 15%.

Breaking opaque predicates

Breaking opaque predicates

$$
\begin{array}{l}
\ldots \\
x_1 \leftarrow \cdots; \\
x_2 \leftarrow \cdots; \\
\ldots \\
b \leftarrow f(x_1, x_2, \ldots); \\
\textbf{if}\ \ b\ \ \textbf{goto}\ \ \ldots
\end{array}
$$

1. find the instructions that make up $f(x_1, x_2, \ldots)$;
2. find the inputs to f, i.e. $x_1, x_2 \ldots$;
3. find the range of values R_1 of x_1,...;
4. compute the outcome of f for all input values;
5. kill the branch if $f \equiv true$.

Breaking opaque predicates

```
int x = some complicated expression;
int y = 42;
z = ...
boolean b = (34*y*y-1)==x*x;
if b goto ...
```

1. Compute a backwards slice from `b`,
2. Find the inputs (`x` and `y`),
3. Find range of x and y,
4. Use number-theory/brute force to determine $b \equiv$ `false`.

Breaking $\forall x \in \mathbb{Z} : n | p(x)$

- Mila Dalla Preda:

- Attack opaque predicates confined to a single basic block.

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- Assume that the instructions that make up the predicate are contiguous.
- Start at a conditional jump instruction j and incrementally extend it with the $1, 2, \ldots$ instructions until an opaque predicate (or beginning of basic block) is found.
- Brute force evaluate, or use abstract interpretation.

Breaking $\forall x \in \mathbb{Z} : 2|(x^2 + x)$

Opaquely true predicate $\forall x \in \mathbb{Z} : 2|(x^2 + x)$:

(1) (2) (3) (4)

```
x = ...;
y = x*x;
y = y + x;
y = y % 2;
b = y==0;
if b ...
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```

(3)

```
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(4)

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(2)

```
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```

(3)

```
x = ...;
y = x*x;
y = y + x;
y = y % 2;
b = y==0;
if b ...
```

(4)

```
x = ...;
y = x*x;
y = y + x
y = y % 2
b = y==0;
if b ...
```

Using Abstract Interpretation

Consider the case when `x` is an even

```
x = even number;
y = x * x;
y = y + x;
z = y % 2;
b = z==0;
if b ...
```

$$
\begin{array}{lll}
\texttt{x} & = & \textit{even}\,; \\
\texttt{y = x } *_a \texttt{ x} & = & \textit{even} *_a \textit{even} = \textit{even}\,; \\
\texttt{y = y } +_a \texttt{ x} & = & \textit{even} +_a \textit{even} = \textit{even}\,; \\
\texttt{z = y } \%_a \texttt{ 2} & = & \textit{even} \bmod 2 = 0\,; \\
\texttt{b = z==0;} & = & \texttt{true} \\
\texttt{if b ...} & &
\end{array}
$$

Using Abstract Interpretation

Consider the case when x starts out being odd:

```
x = odd number;
y = x * x;
y = y + x;
z = y % 2;
b = z==0;
if b ...
```

$\Rightarrow$

`x` = odd;
`y = x` $*_a$ `x` = $\mathit{odd} *_a \mathit{odd} = \mathit{odd}$;
`y = y` $+_a$ `x` = $\mathit{odd} +_a \mathit{odd} = \mathit{even}$;
`z = y` $\%_a$ `2` = $\mathit{even} \bmod 2 = 0$;
`b = z==0;` = `true`
`if b ...`

- Regardless of whether x's initial value is even or odd, b is true!

Breaking $\forall x \in \mathbb{Z} : n | p(x)$

- Regardless of whether `x`'s initial value is even or odd, `b` is true!

Breaking $\forall x \in \mathbb{Z} : n|p(x)$

- Regardless of whether `x`'s initial value is even or odd, `b` is true!
- You've broken the opaque predicate, efficiently!!

Breaking $\forall x \in \mathbb{Z} : n | p(x)$

- Regardless of whether `x`'s initial value is even or odd, `b` is true!
- You've broken the opaque predicate, efficiently!!
- By constructing different abstract domains, Algorithm REPMBG is able to break all opaque predicates of the form $\forall x \in \mathbb{Z} : n | p(x)$ where $p(x)$ is a polynomial.

In-Class Exercise

1. An obfuscator has inserted the opaquely true predicate $\forall x \in \mathbb{Z} : 2|(2x+4)$:

```
x = ...;
if ((((2*x+4) % 2) == 0)^T) {
    some statement
}
```

Or, in simpler operations:

```
x = ...;
y = 2 * x;
y = y + 4;
z = y % 2;
b = z==0;
if b ...
```

2. Play we're an attacker!

3. Do a symbolic evaluation, using these rules:

x	y	$x *_a y$
even	*even*	*even*
even	*odd*	*even*
odd	*even*	*even*
odd	*odd*	*odd*

x	y	$x +_a y$
even	*even*	*even*
even	*odd*	*odd*
odd	*even*	*odd*
odd	*odd*	*even*

x	$x \bmod_a 2$
even	0
odd	1

4. First, let's assume that `x` is even.

```
x = even;
y = 2 * x;
y = y + 4;
z = y % 2;
b = z==0;
if b ...
```

$\texttt{x} = \textit{even};$

$\texttt{y} = \texttt{2} *_a \texttt{x} =$

$\texttt{y} = \texttt{y} +_a \texttt{4} =$

$\texttt{z} = \texttt{y} \,\%_a\, \texttt{2} =$

$\texttt{b = z==0;} =$

`if b ...`

5. Now, let's assume that `x` is odd.

```
x = odd;
y = x * x;
y = y + x;
z = y % 2;
b = z==0;
if b ...
```

$\Rightarrow$

$\texttt{x} = \mathit{odd};$	
$\texttt{y = 2} *_a \texttt{x} =$	
$\texttt{y = y} +_a \texttt{4} =$	
$\texttt{z = y} \%_a \texttt{2} =$	
$\texttt{b = z==0;} =$	
`if b ...`	

Integer Arithmetic

Encoding Integer Arithmetic

$$
\begin{aligned}
x + y &= x - \neg y - 1 \\
x + y &= (x \oplus y) + 2 \cdot (x \wedge y) \\
x + y &= (x \vee y) + (x \wedge y) \\
x + y &= 2 \cdot (x \vee y) - (x \oplus y)
\end{aligned}
$$

- `www.hackersdelight.org`

Integer Arithmetic – Example

- One possible encoding of

```
z = x + y + w
```

is

```
z = (((x ^ y) + ((x & y) << 1)) | w) +
    (((x ^ y) + ((x & y) << 1)) & w);
```

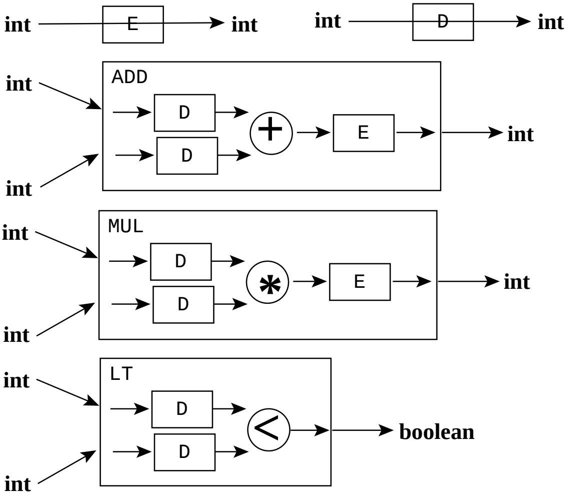
- Many others are possible, which is good for diversity.

Transforming Integers — The identity transformation

```
typedef int T1;
T1 E1(int e) {return e;}
int D1(T1 e) {return e;}
T1 ADD1(T1 a, T1 b) {return E1(D1(a)+D1(b));}
T1 MUL1(T1 a, T1 b) {return E1(D1(a)*D1(b));}
BOOL LT1(T1 a, T1 b) {return D1(a)<D1(b);}
```

- `E1` transforms cleartext integers into the obfuscated representation,
- `D1` transforms obfuscated integers into cleartext,
- `ADD1`, etc., perform operations in obfuscated space.

Transforming Integers — The identity transformation



Linear Transformation I

- We have 3 integer variables `x,y,z`, and we want to encode them with a linear transformation:

$$
\begin{aligned}
x' &= a \cdot x + b \\
y' &= a \cdot y + b \\
z' &= a \cdot z + b
\end{aligned}
$$

- Let a be an odd constant, and b a random constant.
- Let's pick $a = 7,\ b = 5$.

Linear Transformation II

```
int E(int e) {return a*e + b;}
int D(int e) {return ?;}
int ADD(int a, int b) {return ?;}
int MUL(int a, int b) {return ?;}
BOOL LT(int a, int b) {return a<b;}
```

- We need to solve for x:

$$
\begin{aligned}
x' &= a \cdot x + b \\
x &= a^{-1} \cdot x' - a^{-1} \cdot b
\end{aligned}
$$

Linear Transformation III

- Remember, all arithmetic is done mod 2^{32}!

$$
\begin{aligned}
x' &= a \cdot x + b \\
x &= a^{-1} \cdot x' - a^{-1} \cdot b \\
a &= 7 \\
a^{-1} &= 3067833783
\end{aligned}
$$

- Why???

Linear Transformation IV

- Why??? Well, because

$$3067833783 \cdot 7 \bmod 2^{32} = 1$$

- Why??? Because Euclid's Extended Algorithm tells us

$$\gcd(7, 2^{32}) = 3067833783 \cdot 7 + 2 \cdot 2^{32} = 1$$

- And, since $2 \cdot 2^{32} \bmod 2^{32} = 0$, we get

$$3067833783 \cdot 7 = 1 \bmod 2^{32}$$

  I.e., 3067833783 is the inverse of 7, mod 2^{32}.

Linear Transformation V

- We compute $a^{-1} \cdot b$

$$a^{-1} \cdot b \;=\; 3067833783 \cdot 5 \bmod 2^{32}$$

- And now we can encode and decode integers:

```
int E(int e) {return 7*e + 5;}
int D(int e) {return 3067833783*e - 2454267027;}
int ADD(int a, int b) {return ?;}
int MUL(int a, int b) {return ?;}
BOOL LT(int a, int b) {return a<b;}
```

Linear Transformation VI

- Let's try an example, 10:

$$
\begin{aligned}
E(10) &= (7 * 10 + 5) \bmod 2^{32} \\
&= 75 \\
D(75) &= (3067833783 \cdot 75 - 2454267027) \bmod 2^{32} \\
&= 1
\end{aligned}
$$

- So, now we can encode and decode integers, using the linear formula $x' = a \cdot x + b$!

Linear Transformation VII (a)

What about addition in the encoded domain?

```
int E(int e) {return 7*e + 5;}
int D(int e) {return 3067833783*e - 2454267027;}
int ADD(int a, int b) {return ?;}
```

$$
\begin{aligned}
E(x) + E(y) &= E(D(E(x)) + D(E(y))) \\
&= E((a^{-1} \cdot x - a^{-1} \cdot b) + \\
&\quad (a^{-1} \cdot y - a^{-1} \cdot b)) \\
&= a \cdot (a^{-1} \cdot x - a^{-1} \cdot b) + \\
&\quad (a^{-1} \cdot y - a^{-1} \cdot b) + b \\
&= x - b + y - b + b = x + y - b
\end{aligned}
$$

Linear Transformation VII (b)

- So, we get

```
int ADD(int a, int b) {
    return a + b - 2454267027;
}
```

Linear Transformation VIII

- Example:

```
int main () {
    int x = 10;
    int y = 12;
    int z = x + y;
    printf(z);
}
```

- We get:

```
int main () {
    int x = 7*10 + 5; // 75
    int y = 7*12 + 5; // 89
    int z = 75 + 89 - 5; // 159
    printf(3067833783*z - 2454267027); // 22!
}
```

Exercise: Integer encoding

- Consider again the GCD routine:

```
int gcd(int x, int y) {
    int temp;
    while (true) {
        boolean b = x%y == 0;
        if (b) break;
        temp = x%y;
        x = y;
        y = temp;
    }
}
```

- Use the $E()/D()$ scheme above to encode the integer variables.
- What kind of encoding would work well here?

Another Number-theoretic trick

```
#define N4 (53*59)
int E4(int e,int p) {return p*N4+e;}
int D4(int e) {return e%N4;}
int ADD4(int a, int b) {return a+b;}
int MUL4(int a, int b) {return a*b;}
BOOL Lint(int a, int b) {return D4(a)<D4(b);}
```

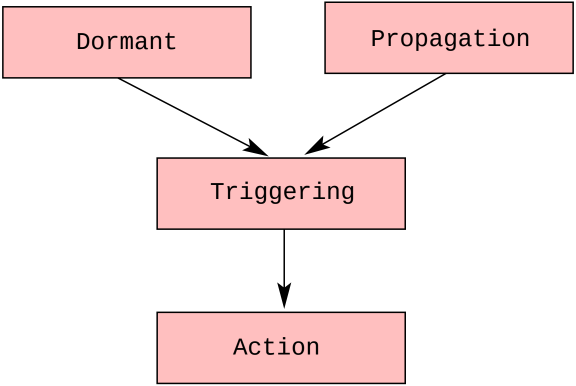
- An integer y is represented as $N * p + y$, where N is the product of two close primes, and p is a random value.
- Addition and multiplication are performed in obfuscated space.
- Comparisons require deobfuscation.

Computer Viruses

Computer Viruses

- Viruses
  1. are self-replicating;
  2. attach themselves to other files;
  3. requires user assistance to to replicate.
  4. use obfuscation to hide!

Computer Viruses: Phases



Computer Viruses: Phases…

- Dormant — lay low, avoid detection.
- Propagation — infect new files and systems.
- Triggering — decide to move to action phase
- Action — execute malicious actions, the payload.

Virus Types

- Program/File virus:

Virus Types

- Program/File virus:
  - Attaches to: program object code.

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  - Run when: program executes.
  - Propagates by: program sharing.

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  - Attaches to: document (.doc,.pdf,...).

Virus Types

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  - Attaches to: program object code.
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  - Attaches to: document (.doc,.pdf,...).
  - Run when: document is opened.

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- Program/File virus:
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  - Run when: document is opened.
  - Propagates by: emailing documents.
- Boot sector virus:
  - Attaches to: hard drive boot sector.

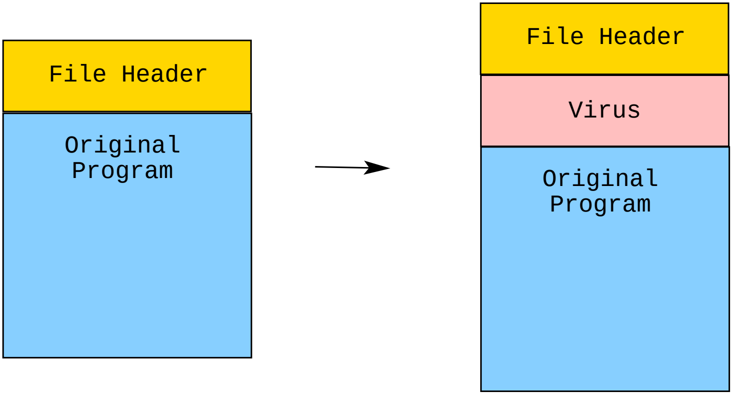
Virus Types

- Program/File virus:
  - Attaches to: program object code.
  - Run when: program executes.
  - Propagates by: program sharing.
- Doocument/Macro virus:
  - Attaches to: document (.doc,.pdf,. . .).
  - Run when: document is opened.
  - Propagates by: emailing documents.
- Boot sector virus:
  - Attaches to: hard drive boot sector.
  - Run when: computer boots.

Virus Types

- Program/File virus:
  - Attaches to: program object code.
  - Run when: program executes.
  - Propagates by: program sharing.
- Doocument/Macro virus:
  - Attaches to: document (.doc,.pdf,. . .).
  - Run when: document is opened.
  - Propagates by: emailing documents.
- Boot sector virus:
  - Attaches to: hard drive boot sector.
  - Run when: computer boots.
  - Propagates by: sharing floppy disks.

Computer Viruses: Propagation



Virus Defenses

- Signatures: Regular expressions over the virus code used to detect if files have been infected.
- Checking can be done
  1. periodically over the entire filesystem;
  2. whenever a new file is downloaded.

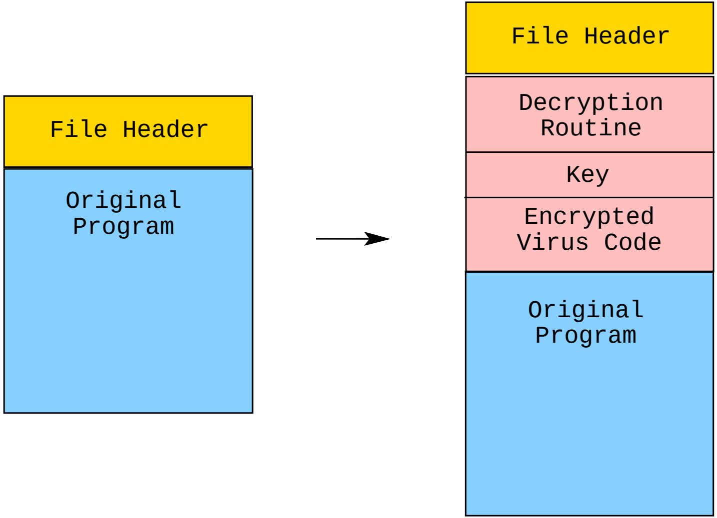
Virus Countermeasures

- Viruses need to protect themselves against detection.
- This means hiding any distringuishing features, making it hard to construct signatures.
- By encrypting its payload, the virus hides its distinguishing features.
- Encryption is often no more than xor with a constant.

Virus Countermeasures: Encryption

- By encrypting its payload, the virus hides its distinguishing features.
- The decryption routine itself, however, can be used to create a signature!

Computer Countermeasures: Encryption...



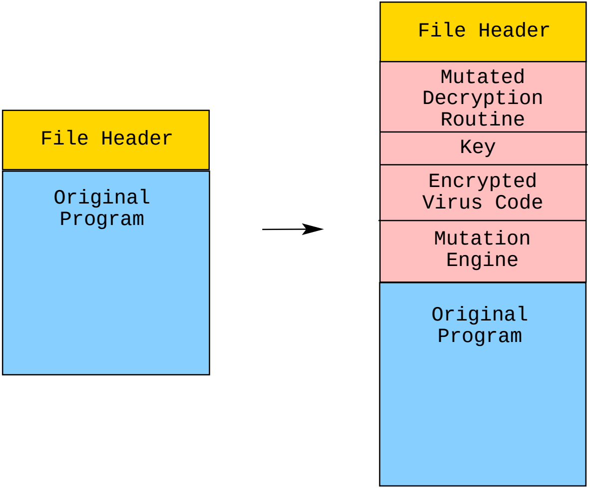
Virus Countermeasures: Polymorphism

- Each variant is encrypted with a different key.

Virus Countermeasures: Metamorphism

- To prevent easy creation of signatures for the decryption routine, metamorphic viruses will mutate the decryptor, for each infection.
- The virus contains a mutation engine which can modify the decryption code while maintaining its semantics.

Computer Countermeasures: Metamorphism...



Virus Countermeasures: Metamorphism...

- To counter metamorphism, virus detectors can run the virus in an emulator.
- The emulator gathers a trace of the execution.
- A virus signature is then constructed over the trace.
- This makes it easier to ignore garbage instructions the mutation engine may have inserted.

Virtualization

Interpreters

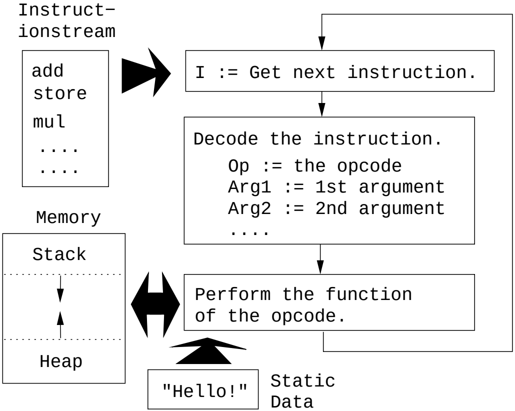
- An interpreter is program that behaves like a CPU, but which has its own
  - instruction set,
  - program,
  - program counter
  - execution stack
- Many programming languages are implemented by constructing an interpreter for them, for example Java, Python, Perl, etc.

Interpreters for Obfuscation

```
void foo() {
   ...
   a = a + 5;
   ...
}
```

```
prog=[ADD,...];
stack=...;
int pc=...;
int sp=...;
while (1)
   switch (prog[pc])
      case ADD: ...
        stack[sp]=...
        pc++; sp--;
```

Interpreter Engine



Diversity

- Viruses want diversity in the code they generate.
- This means, every version of the virus should look different, so that they are hard for the virus detector to find.
- We want the same when we protect our programs!

Tigress Diversity

- tigress.cs.arizona.edu
- Interpreter diversity:
  1. 8 kinds of instruction dispatch: switch, direct, indirect, call, ifnest, linear, binary, interpolation
  2. 2 kinds of operands: stack, registers
  3. arbitrarily complex instructions
  4. operators are randomized
- Along with: flatten, merge functions, split functions, opaque predicates, etc.

Tigress Diversity

- Every input program generates a unique interpreter.
- A seed sets the random number generator that allows us to generate many different interpreters for the same input program.
- The split transformation can be used to break up the interpreter in pieces, to make it less easy to detect.

In-class Exercise

```
tigress --Transform=Virtualize --Functions=fib \
        --VirtualizeDispatch=switch \
        --out=v1.c test1.c
gcc -o v1 v1.c

tigress --Transform=Virtualize --Functions=fib \
        --VirtualizeDispatch=indirect \
        --out=v2.c test1.c
gcc -o v2 v2.c
```

In-class Exercise

```
tigress --Transform=Virtualize --Functions=fib \
          --VirtualizeDispatch=switch \
       --Transform=Virtualize --Functions=fib \
          --VirtualizeDispatch=indirect \
       --out=v3.c test1.c
gcc -o v3 v3.c

tigress --Transform=Virtualize --Functions=fib \
         --VirtualizeDispatch=switch \
         --VirtualizeSuperOpsRatio=2.0 \
         --VirtualizeMaxMergeLength=10 \
         --VirtualizeOptimizeBody=true \
         --out=v4.c test1.c
gcc  -o v4 v4.c
```

Attack 1

- Reverse engineer the instruction set!
- Look at the instruction handlers, and figure out what they do:

```
case o233:
    (pc)++;
    s[sp - 1].i = s[sp - 1].i < s[sp].i;
    (sp)--;
    break;
```

- Then recreate the original program from the virtual one.

Counter Attack 1

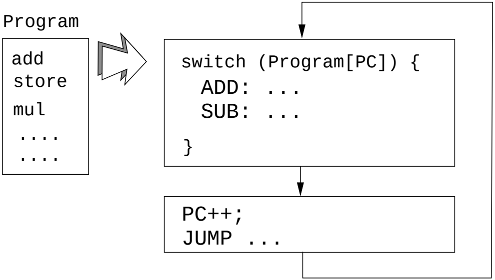
- Make instructions with complex semantics, using super operators:

```
case o98:
    (pc) ++;
    *((int *)s[sp + 0].v) = s[sp + -1].i;
    *((int *)((void *)(l + *((int *)(pc + 4))))) =
        *((int *)((void *)(l + *((int *)pc))));
    s[sp + -1].i = *((int *)((void *)(l + *((int *)(pc + 8))))
        *((int *)(pc + 12));
    s[sp + 0].v = (void *)(l + *((int *)(pc + 16)));
    pc += 20;
    break;
```

- Then recreate the original program from the virtual one.

Attack 2

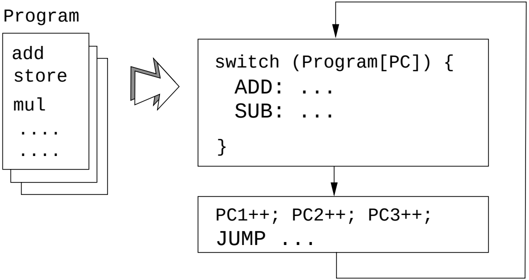
- Dynamic attack: run the program, collect all instructions, look for patterns that look like the virtual PC:



`Trace:switch,ADD,PC++,JUMP,switch,...`

Counter Attack 2

- Tigress can merge several programs, so they execute in tandem, making it harder to detect what is the PC (there are many PCs!).



Discussion

Code Obfuscation — What's it Good For?

- Diversification — make every program unique to prevent malware attacks

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- Data Privacy — make programs hard to understand to protect secret data (keys)

Code Obfuscation — What's it Good For?

- Diversification — make every program unique to prevent malware attacks
- Prevent collusion — make every program unique to prevent diffing attacks
- Code Privacy — make programs hard to understand to protect algorithms
- Data Privacy — make programs hard to understand to protect secret data (keys)
- Integrity — make programs hard to understand to make them hard to change