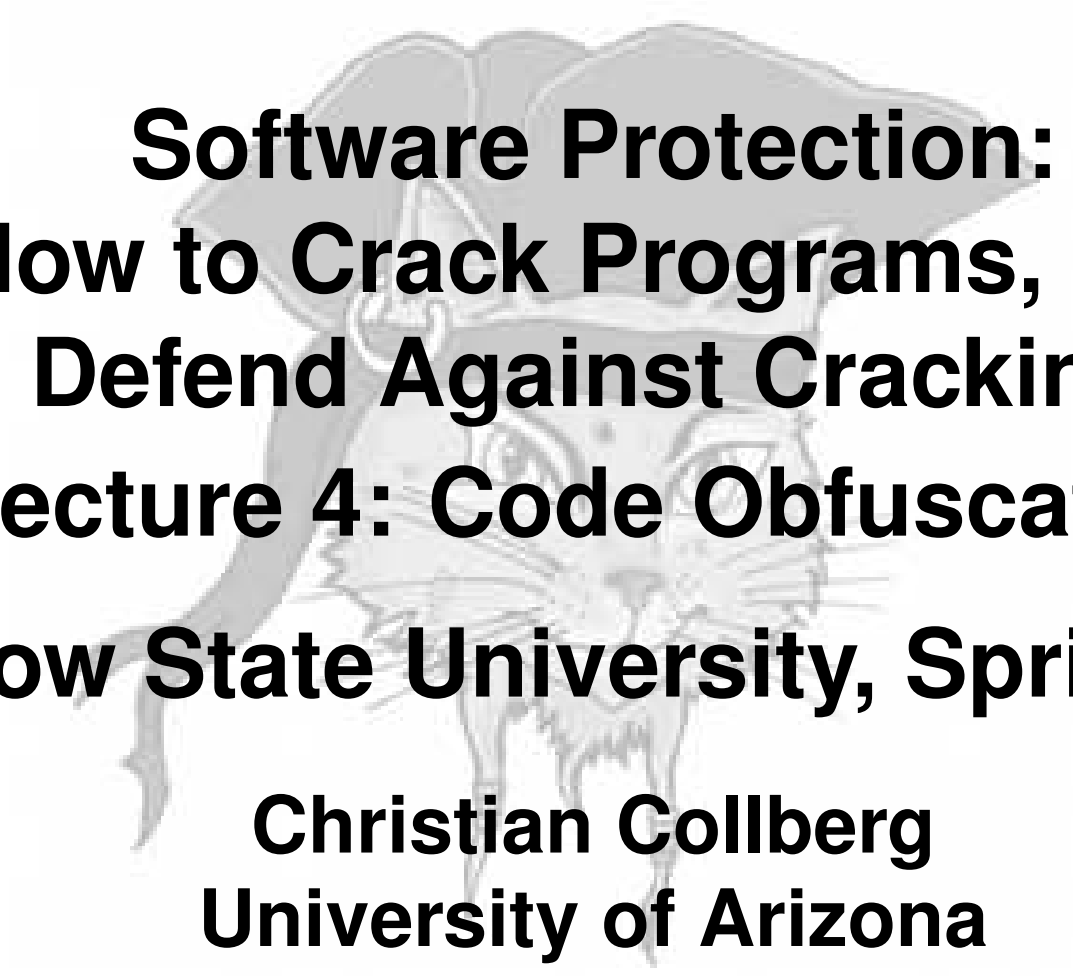

Software Protection: How to Crack Programs, and Defend Against Cracking

Lecture 4: Code Obfuscation

Moscow State University, Spring 2014

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Last week's lecture

- Who needs program analysis?

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- Give two algorithms for disassembly!
- Give some reasons why disassembly is hard!
- What is a script kiddie?

Today's lecture

1. Static obfuscation algorithms
2. Computer viruses
3. Code Diversity

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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  - 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

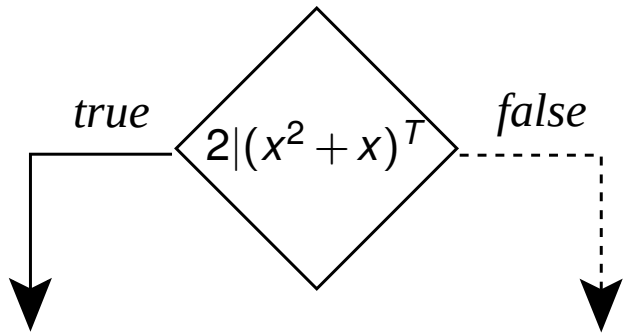
Opaque Expressions

- Graphical notation:

- Building blocks for many obfuscations.

Opaque Expressions

- An opaquely true predicate:



Opaque Expressions

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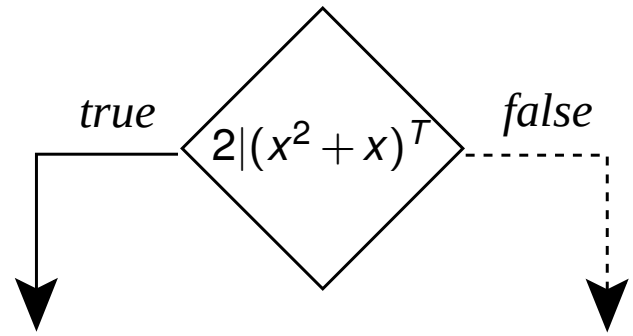

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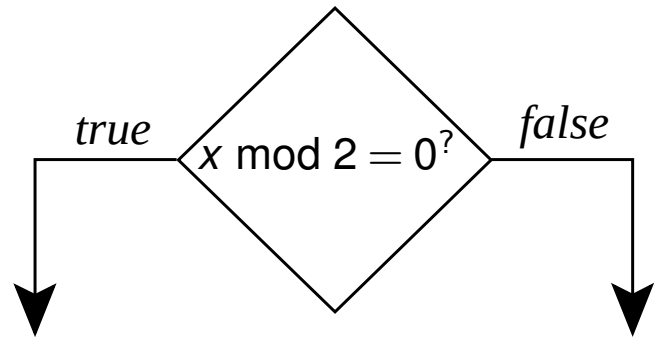

Inserting bogus control-flow

- Insert *bogus* control-flow into a function:
  1. dead branches which will never be taken

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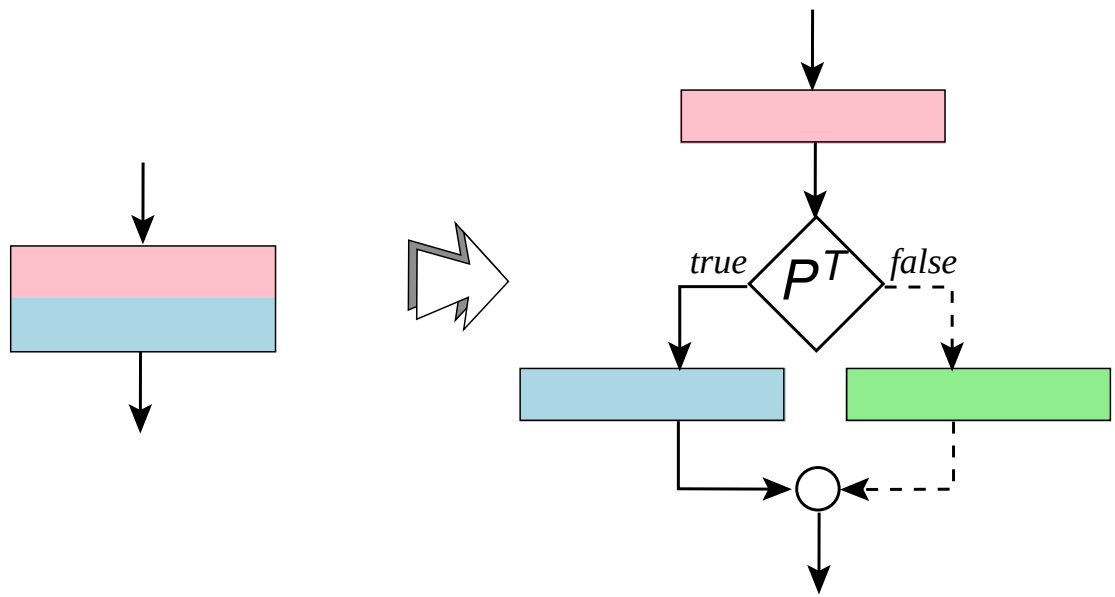
  3. branches which will sometimes be taken and sometimes not, but where this doesn't matter
- The resilience reduces to the resilience of the opaque predicates.

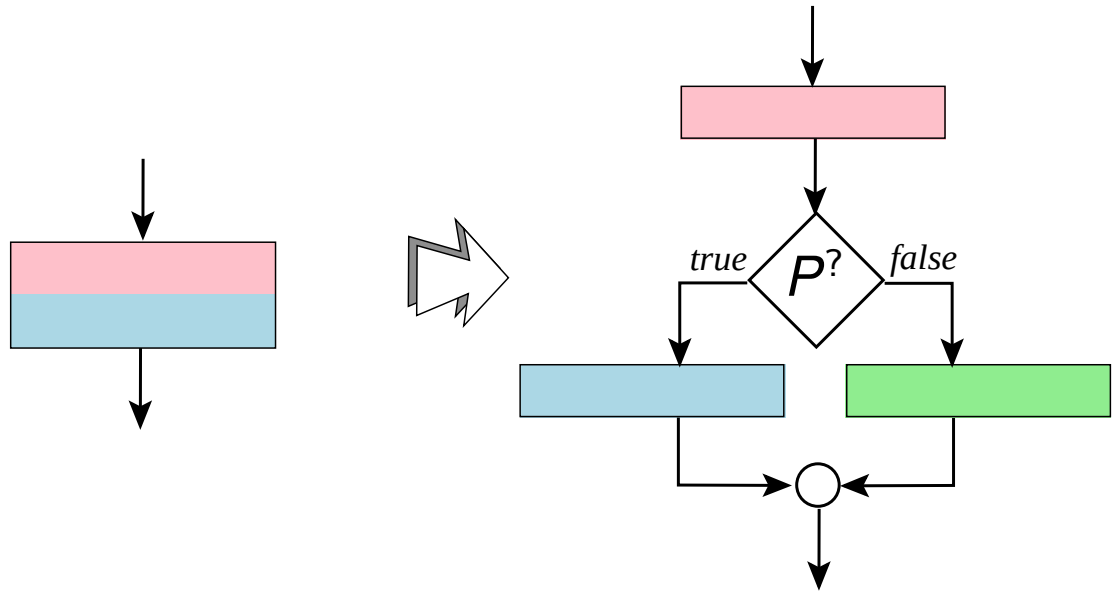
Inserting bogus control-flow

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



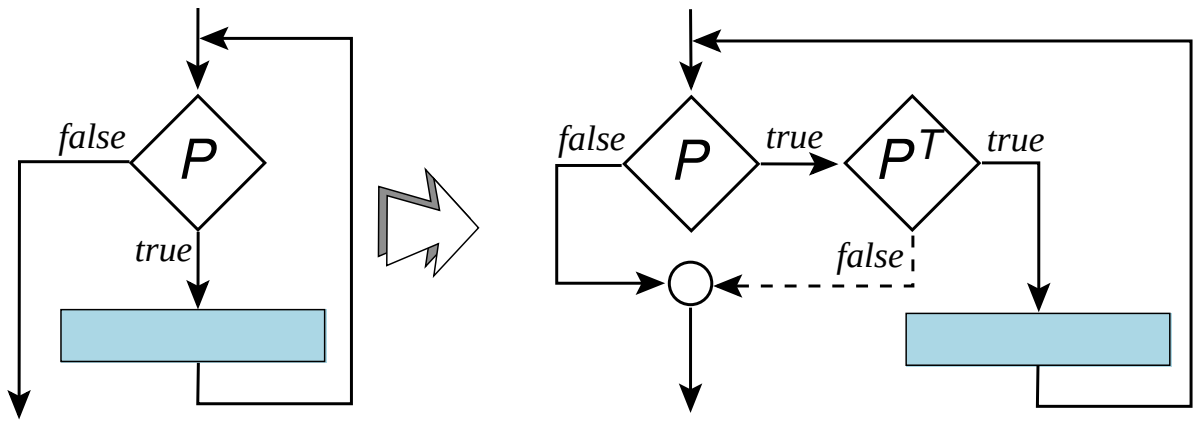
Inserting bogus control-flow

- 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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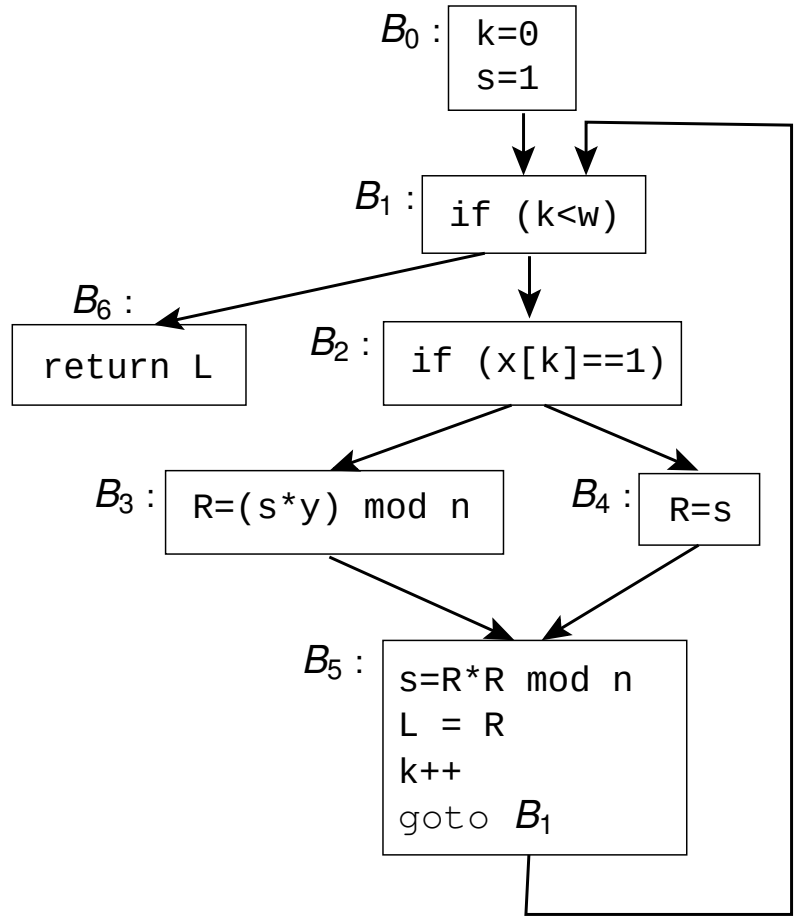
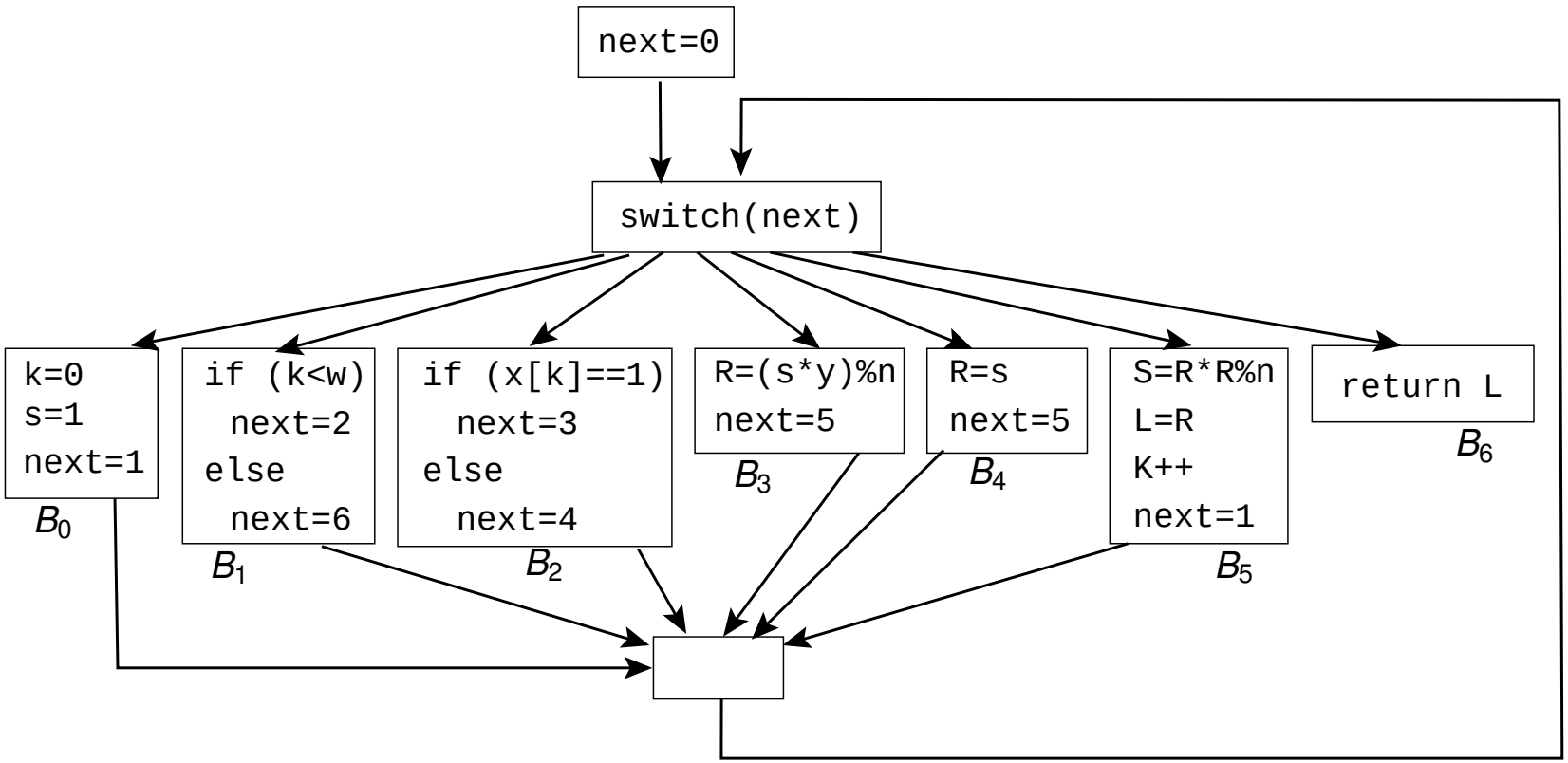
- Chenxi Wang's PhD thesis:

```
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; break;
         case 2 : if (x[k]==1) next=3; else next=4; brea
         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)
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else
next=6
B1
if (x[k]==1)
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else
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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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  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

- Attack:
  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.
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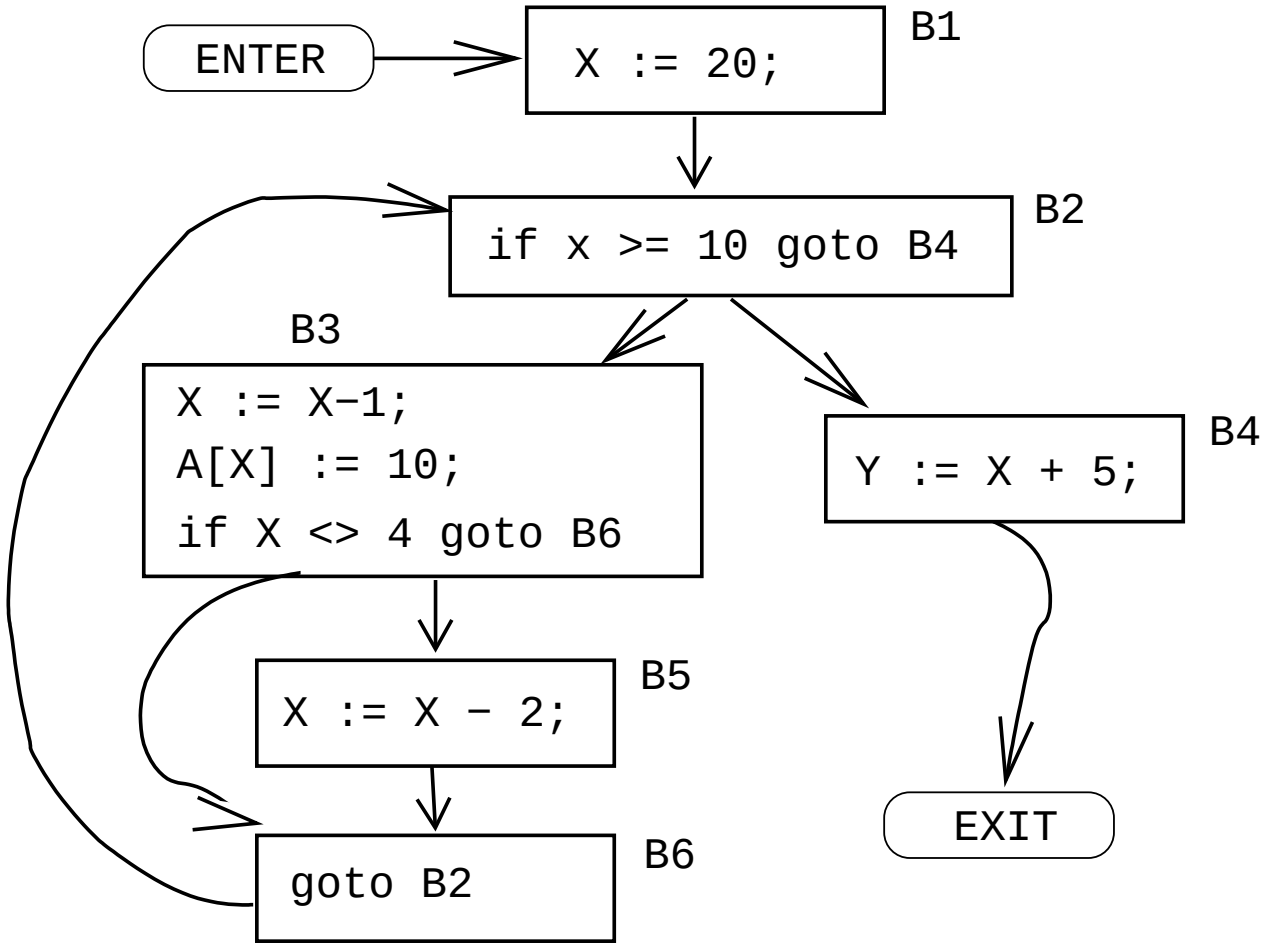
- How does an attacker do this?
  1. use-def data-flow analysis
  2. constant-propagation data-flow analysis

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; brea
            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

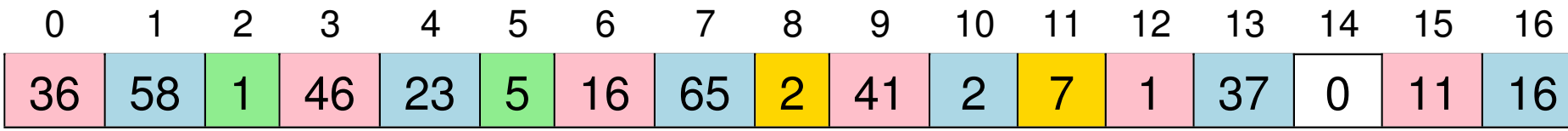
1. Flatten this CFG:



2. Give the source code for the flattened graph above

Constructing Opaque Predicates

Opaque values from array aliasing



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.

```
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;
      }
}
```

Opaque predicates from pointer aliasing

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

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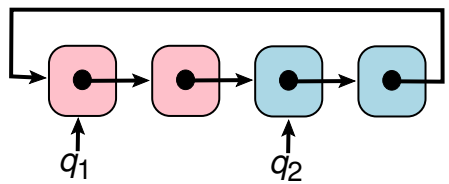
- Of course, these assumptions may be false!

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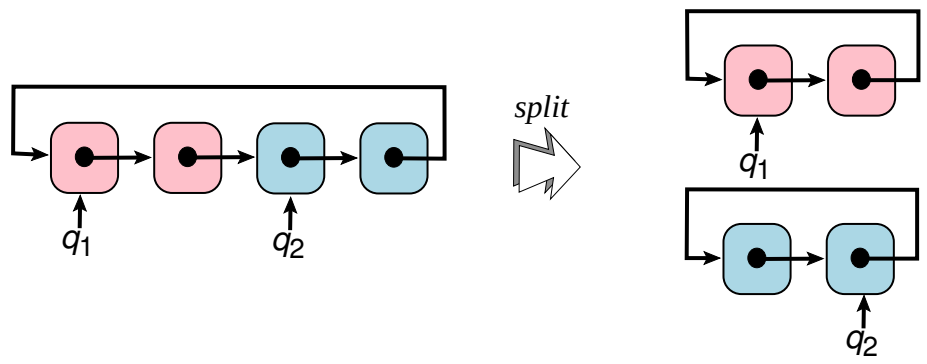
- q_1 and q_2 point into two graphs G_1 (pink) and G_2 (blue):



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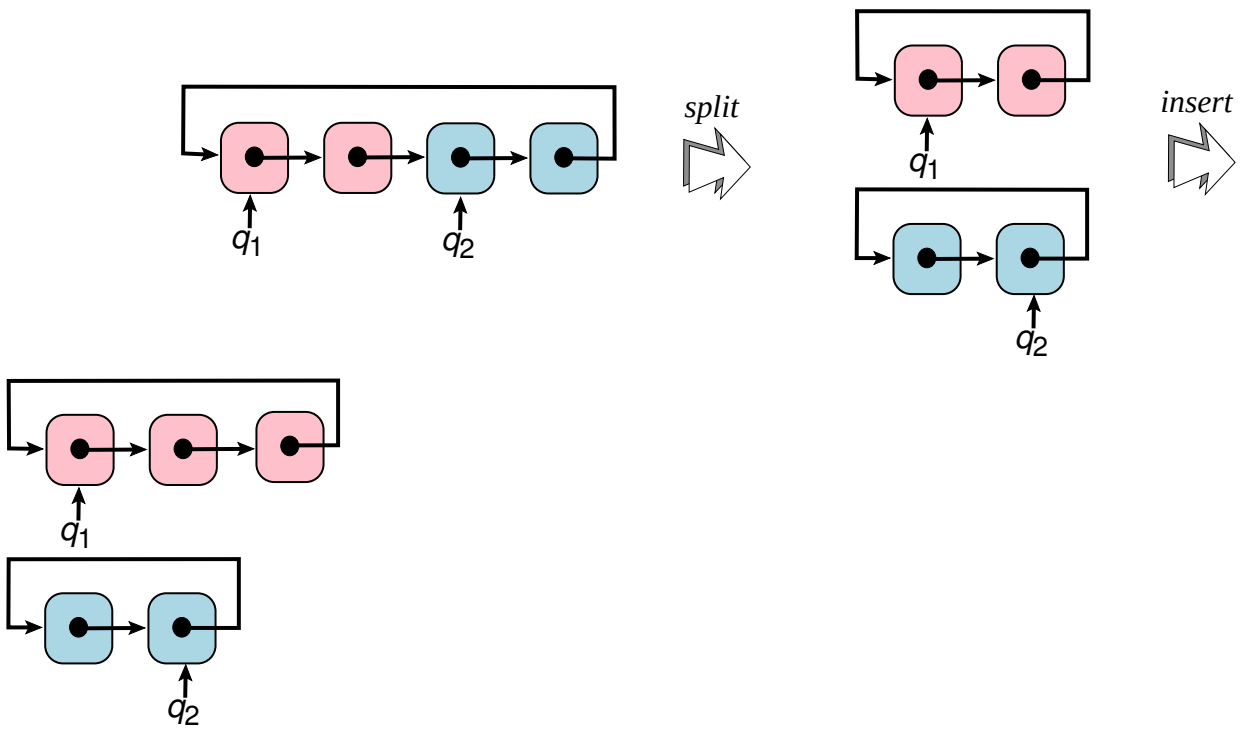

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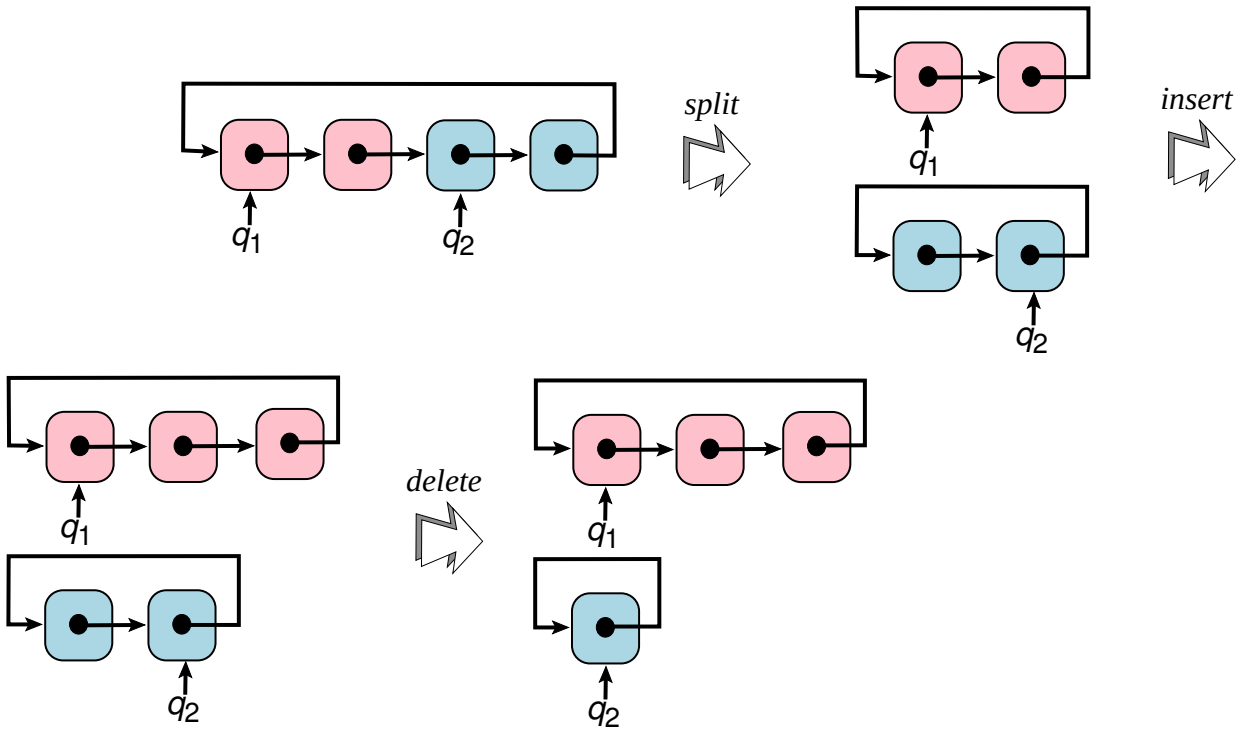

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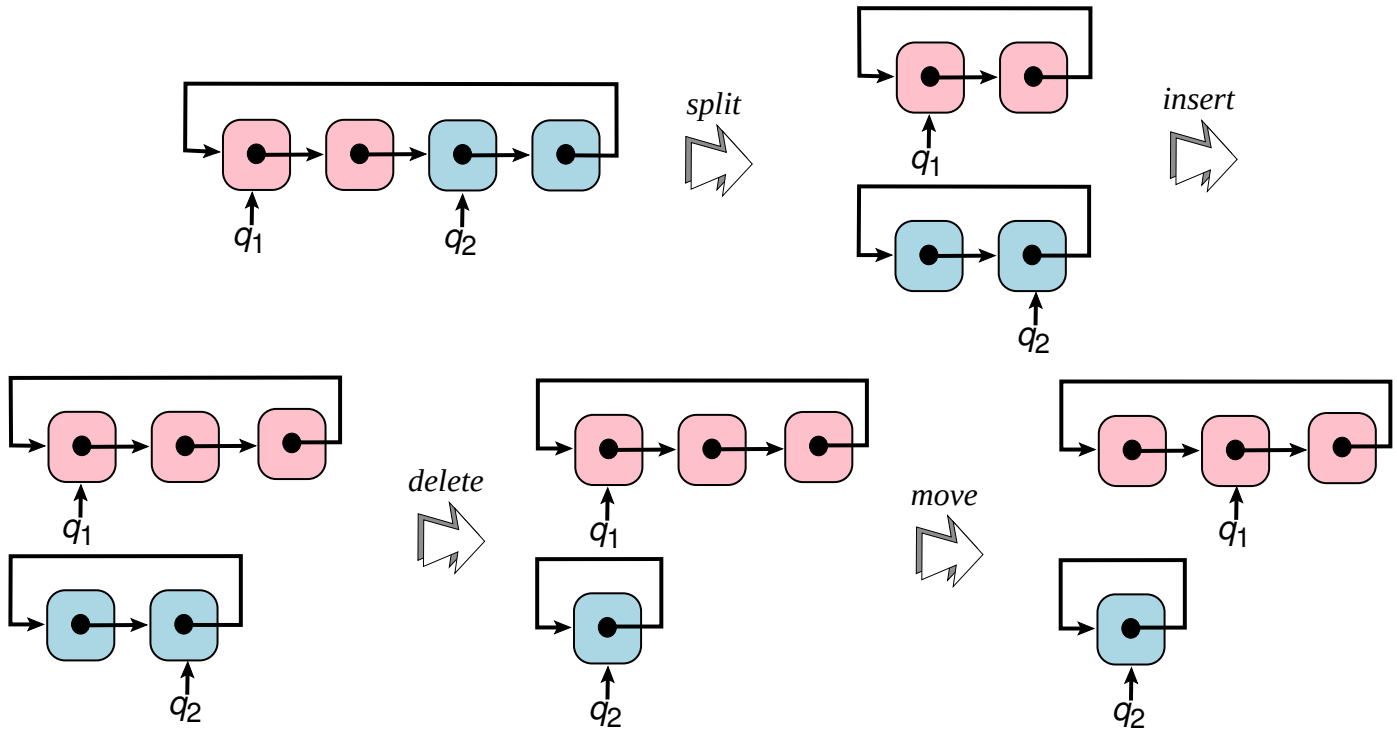

Invariants

- Two invariants:
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Invariants

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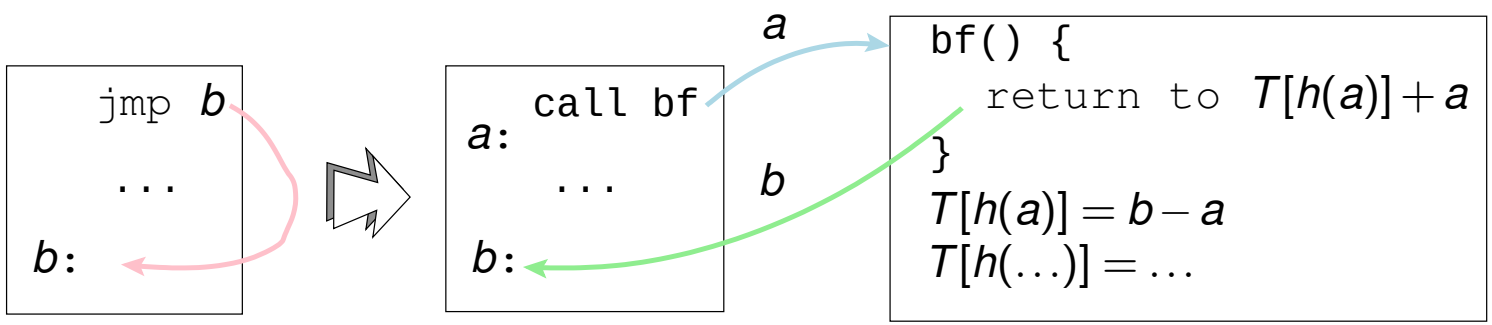
- Perform enough operations to confuse even the most precise alias analysis algorithm,
- Insert opaque queries such as $(q_1 \neq q_2)^T$ into the code.

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

```
...
x1 ← ···;
x2 ← ···;
...
b ← f(x1, x2, ...);
if b goto ...
```

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 $x_1, \ldots$;
4. compute the outcome of f for all input values;
5. kill the branch if $f \equiv \mathit{true}$.

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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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;
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```
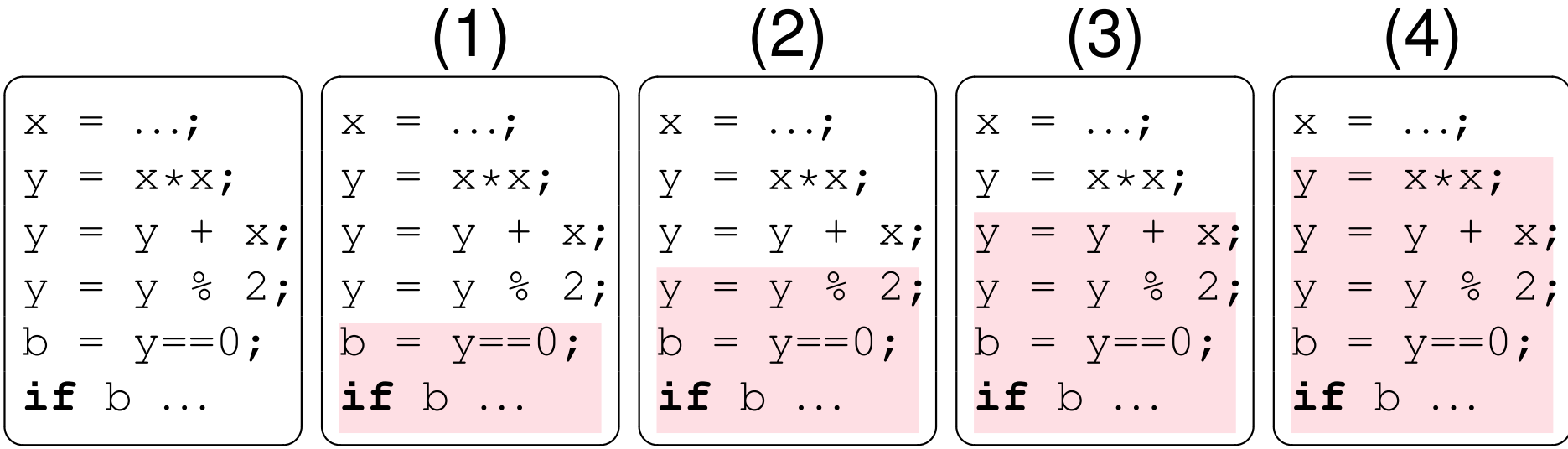

(4)

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

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



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 ...
```

```
x              = even;
y = x *a x     = even *a even = even;
y = y +a x     = even +a even = even;
z = y %a 2     = even mod 2 = 0;
b = z==0;      = true
if b ...
```

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 ...
```

```
x           = odd;
y = x *a x  = odd *a odd = odd;
y = y +a x  = odd +a odd = even;
z = y %a 2  = even mod 2 = 0;
b = z==0;   = true
if b ...
```

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

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

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- 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 ...
```

```
x              = even;
y = 2 *a x     =
y = y +a 4     =
z = y %a 2     =
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 ...
```

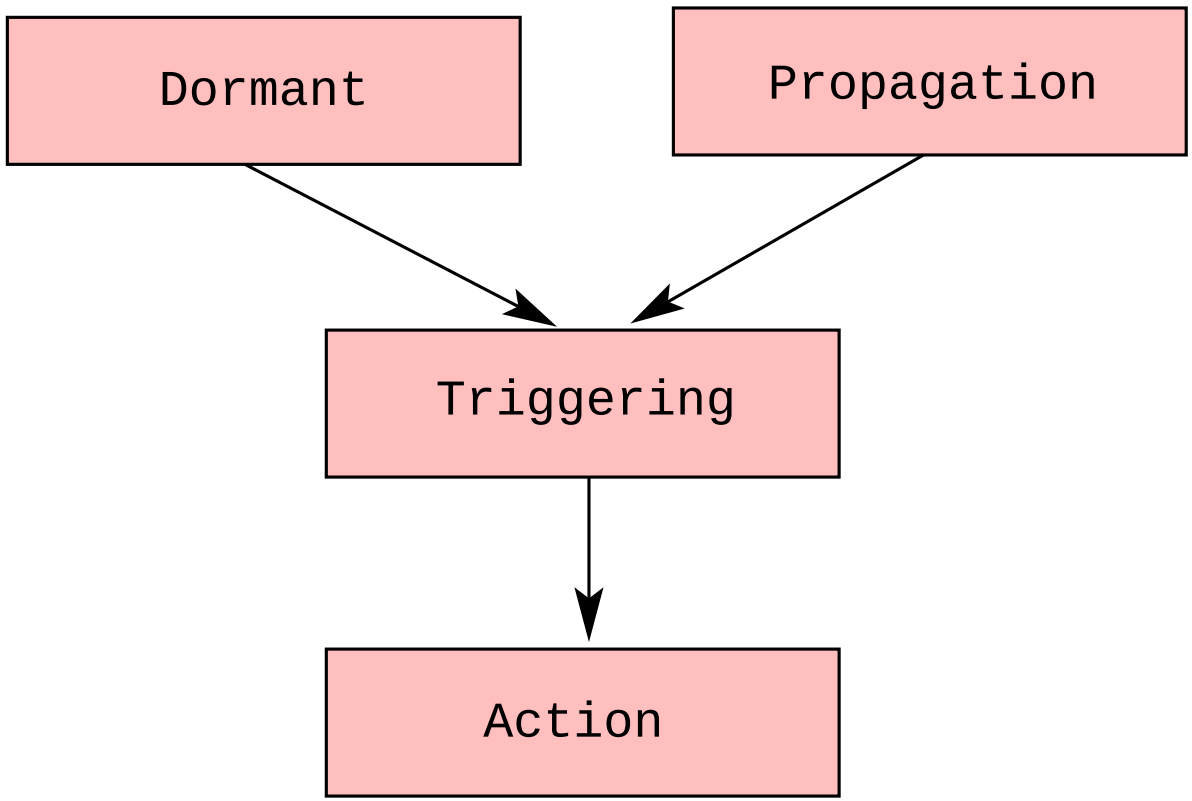
```
x              = odd;
y = 2 *a x     =
y = y +a 4     =
z = y %a 2     =
b = z==0;      =
if b ...
```

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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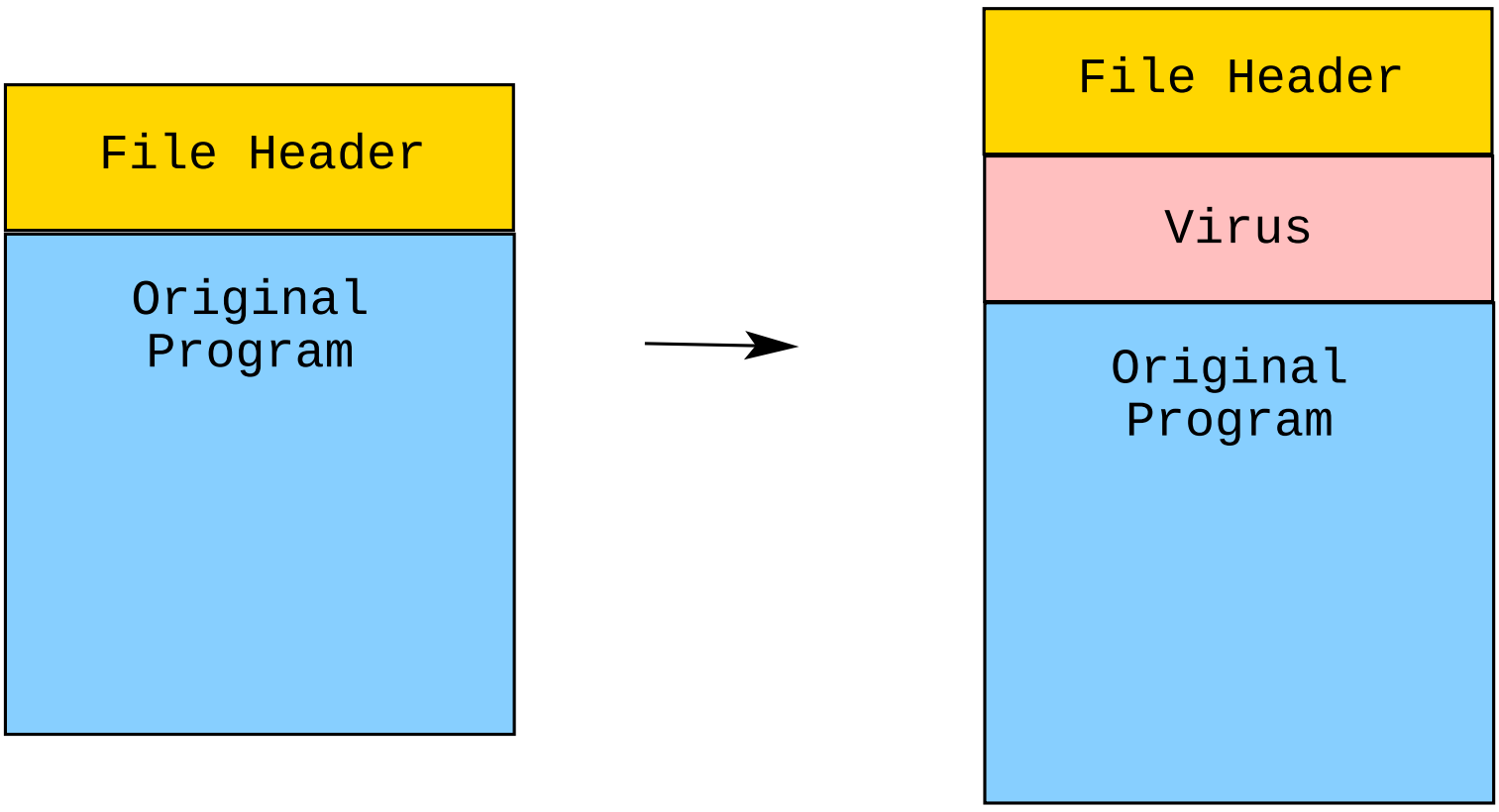
  - Run when: document is opened.
  - Propagates by: emailing documents.
- Boot sector virus:
  - Attaches to: hard drive boot sector.
  - Run when: computer boots.
  - Propagates by: sharing floppy disks.

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.

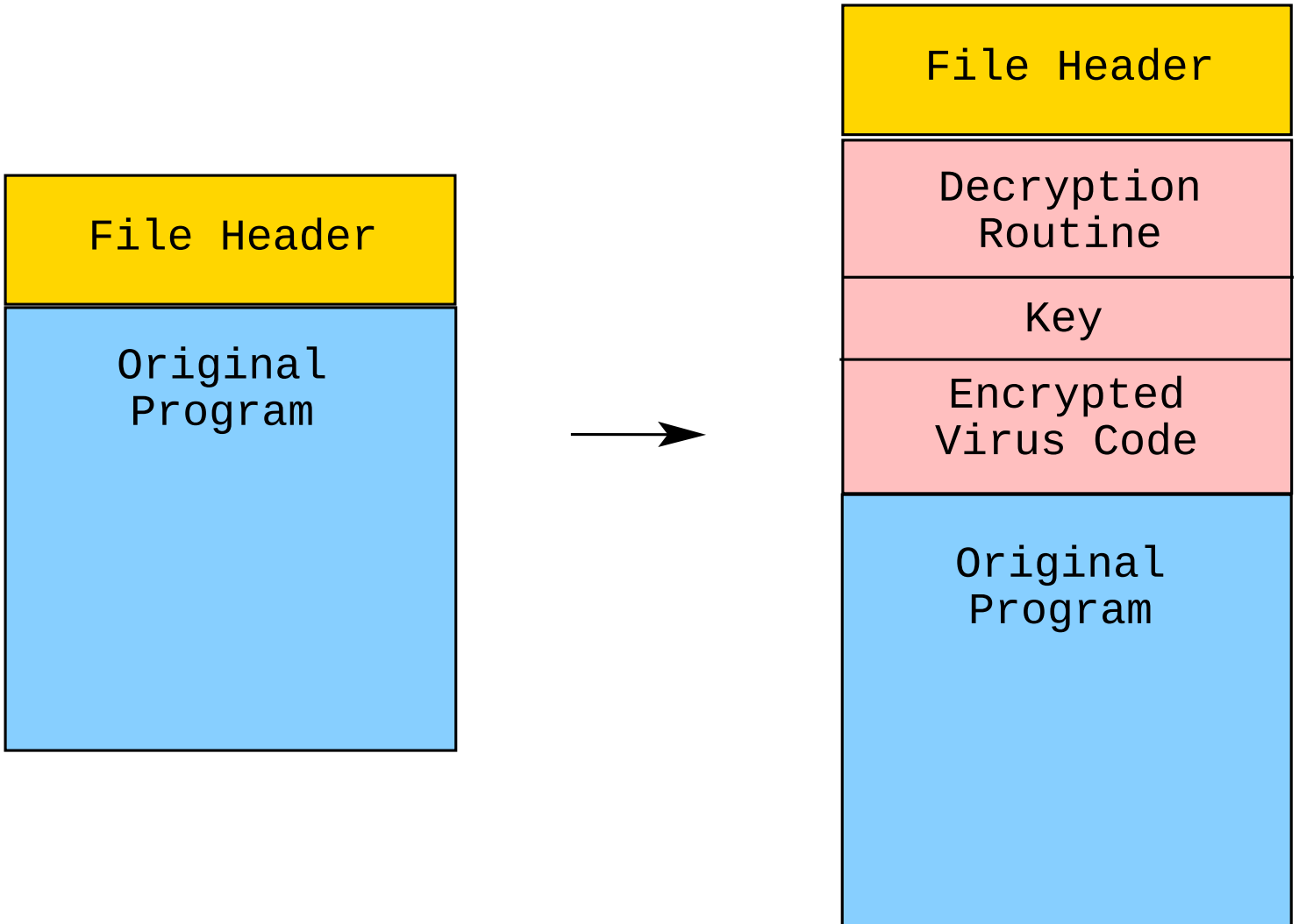
Virus Countermeasures

- 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. . .



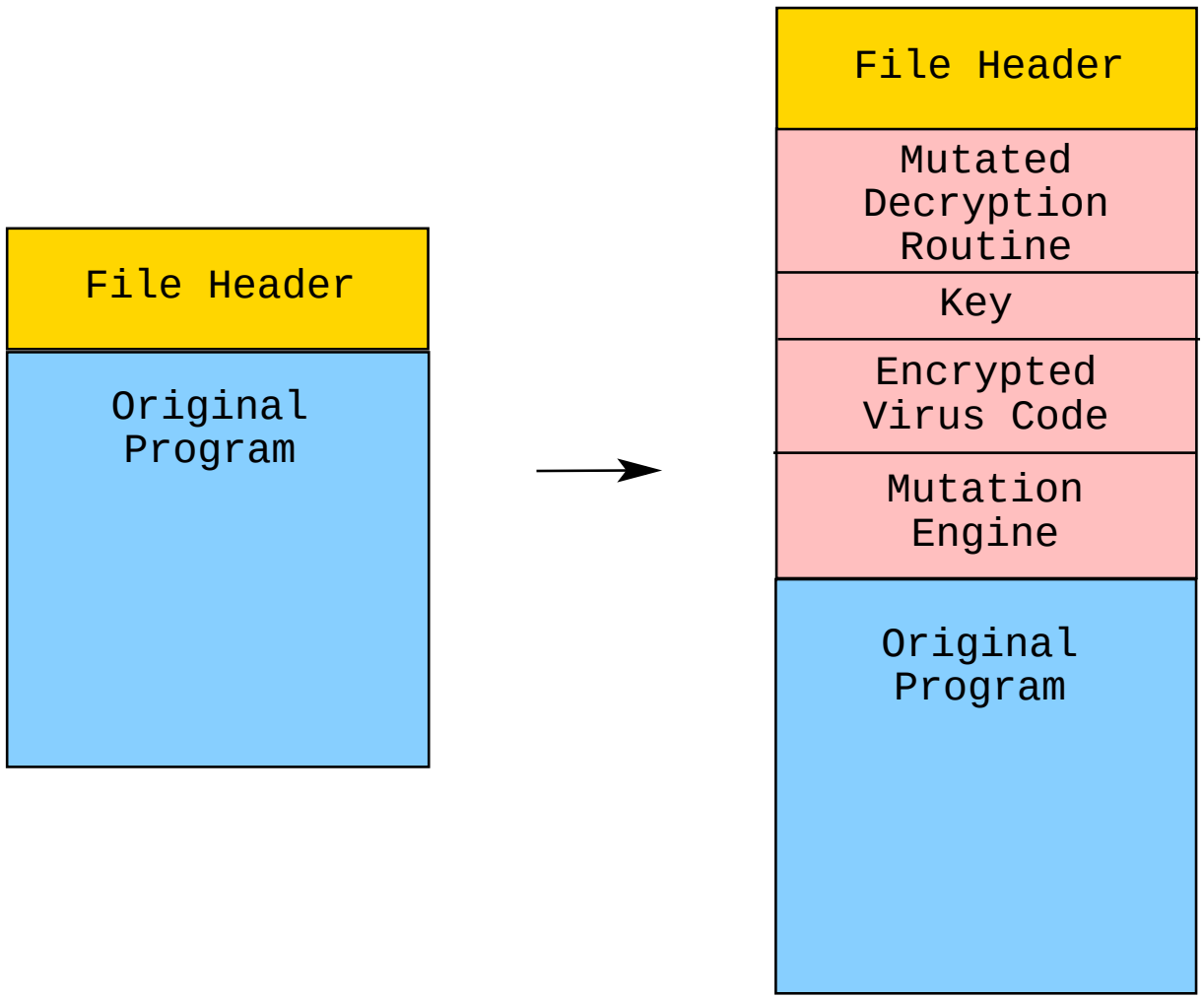
Virus Countermeasures: Polymorphism

- 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

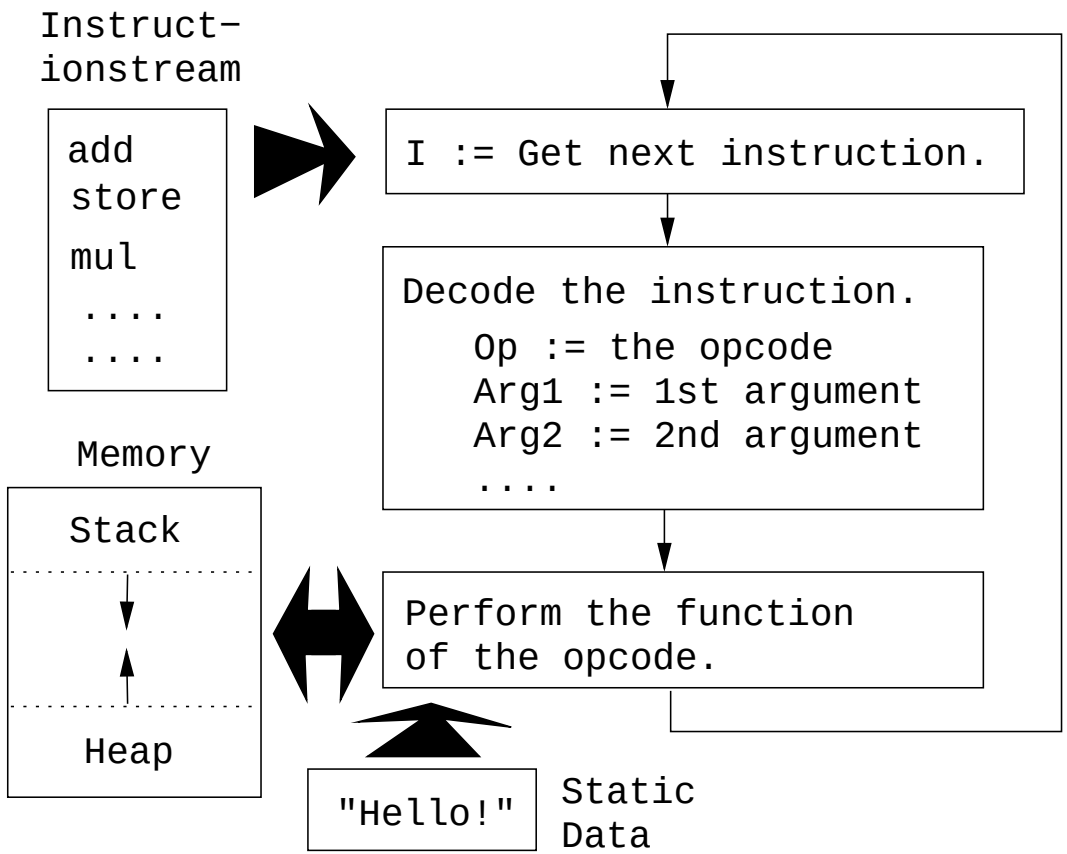
- An interpreter is program that behaves like a CPU, but which has its own
  - instruction set,
  - program,
  - program counter
  - execution stack
- Many programming languages are implemented by constructing an interpreter for them, for example Java, Python, Perl, etc.

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

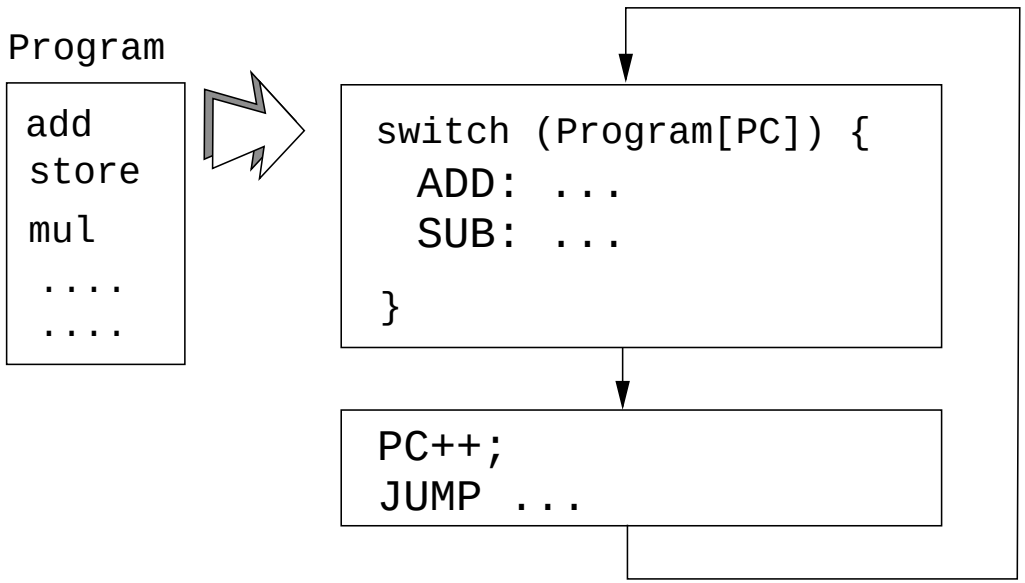
- Make instructions with complex semantics, using super operators:

```
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

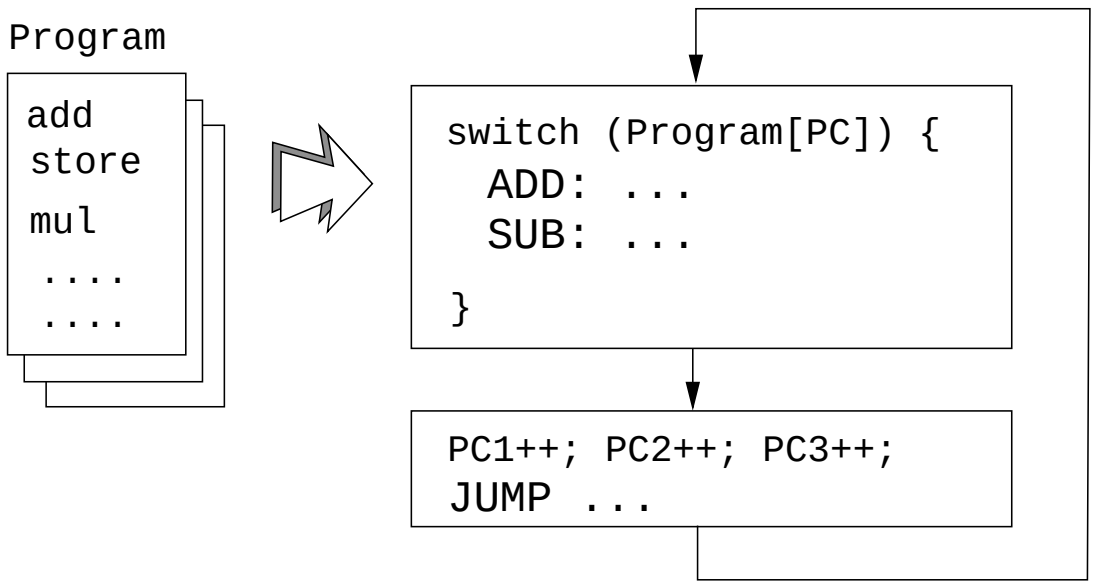
- Dynamic attack: run the program, collect all instructions, look for patterns that look like the virtual PC:




```
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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- 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

Next week's lecture

1. Dynamic obfuscation algorithms
2. Tamperproofing algorithms
3. Please check the website for important announcements:

`www.cs.arizona.edu/~collberg/`

`Teaching/mgu/2014`