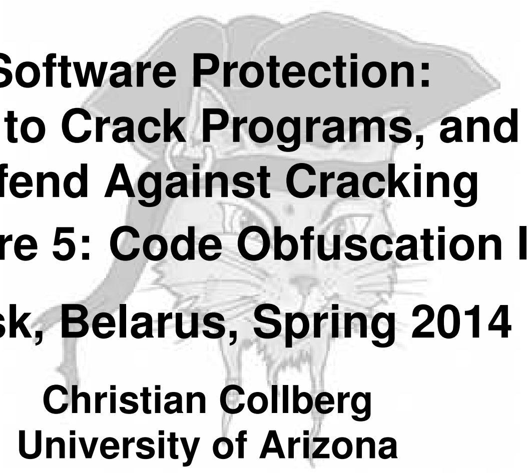

Software Protection: How to Crack Programs, and Defend Against Cracking

Lecture 5: Code Obfuscation II

Minsk, Belarus, Spring 2014

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Dynamic Obfuscation

Static vs. Dynamic obfuscation

- Static obfuscations transform the code prior to execution.

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- Dynamic algorithms transform the program at runtime.

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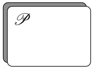
Dynamic Obfuscation: Definitions

- A dynamic obfuscator runs in two phases:
  1. At compile-time transform the program to an initial configuration and add a runtime code-transformer.
  2. At runtime, intersperse the execution of the program with calls to the transformer.

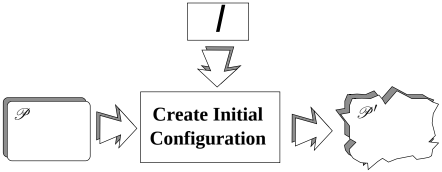
Dynamic Obfuscation: Definitions

- A dynamic obfuscator runs in two phases:
  1. At compile-time transform the program to an initial configuration and add a runtime code-transformer.
  2. At runtime, intersperse the execution of the program with calls to the transformer.
- A dynamic obfuscator turns a “normal” program into a self-modifying one.

Modeling dynamic obfuscation — compile-time



Modeling dynamic obfuscation — compile-time



- Transformer *I* creates $\mathscr{P}$'s initial configuration.

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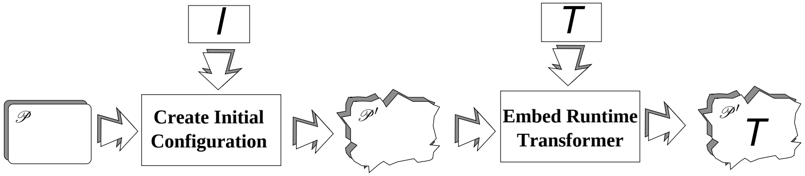
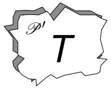


- Transformer I creates $\mathscr{P}$'s initial configuration.
- T is the runtime obfuscator, embedded in $\mathscr{P}'$.

Modeling dynamic obfuscation — runtime



- Transformer T continuously modifies $\mathscr{P}'$ at runtime.

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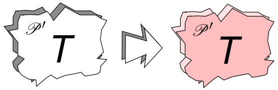

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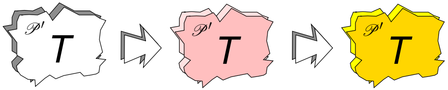

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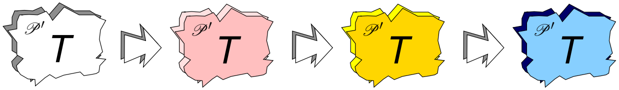

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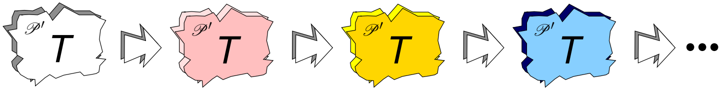

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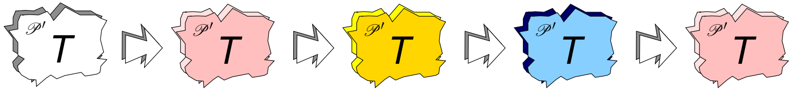
Modeling dynamic obfuscation — runtime



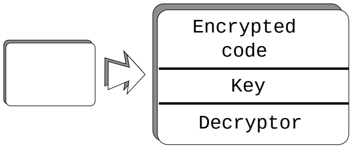
- Transformer T continuously modifies $\mathscr{P}'$ at runtime.
- We'd like an infinite, non-repeating series of configurations.
- In practice, the configurations repeat.

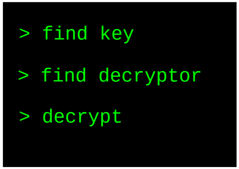
Algorithm Ideas

Basic algorithm ideas

- Build-and-execute: generate code for a routine at runtime, and then jump to it.
- Self-modification: modify the executable code.
- Encryption: The self-modification is decrypting the encrypted code before executing it.
- Move code: Every time the code executes, it is in different location.

File-Level Encryption: Packers

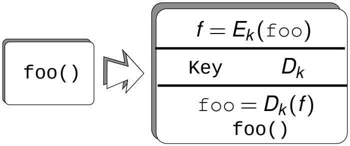




```
> find key

> find decryptor

> decrypt
```

- Packers are simple tools that encrypt the binary, and include a routine that will decrypt at runtime.

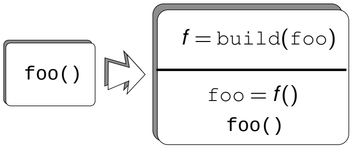
Function-Level Encryption

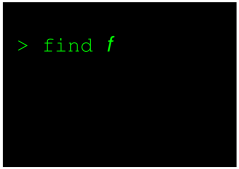


```
> find key
> find D_k
> find f
> decrypt
```

- You can also decrypt a function just before it gets called.

Build-And-Execute

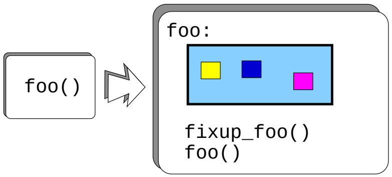


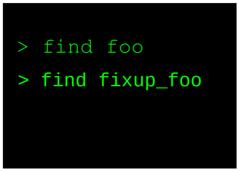


```
> find f
```

- You can generalize “encryption” to any embedded function that constructs the “real” code at runtime.

Self-Modifying Code

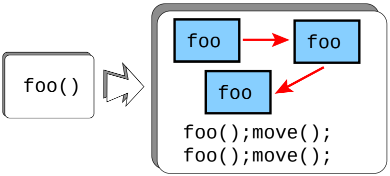




```
> find foo
> find fixup_foo
```

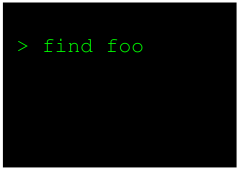
- Leave “holes” in `foo`, fix them just before `foo` gets called.

Move Code Around



```
foo()
```

```
foo();move();
foo();move();
```



```
> find foo
```

- Continously move code around to make it harder to find.

Granularity

- These operations can be applied at different levels of granularity:
  - File-level
  - Function-level
  - Basic block-level
  - Instruction-level

Attack Goals

- The attacker's goal can be to:
  - recover the original code
  - modify the original code

```
int modexp(int y, int x[], int w, int n, int mode) {
    int R, L, k = 0, s = 1, t;
    char* p=&&begin;
    while (p<(char*)&&end) *p++ ^= 99;
    if (mode==1) return 0;
    while (k < w) {
        begin:
            ... ... ...
            ... ... ...
        end:
        k++;
    }
    p=&&begin; while (p<(char*)&&end) *p++ ^= 99;
    return L;
}
int main() {
    makeCodeWritable(···);
    modexp(0, NULL, 0, 0, 1);
    ...
    modexp(···, ···, ···, ···, 0);
}
```

Code Explanation

- The blue code is xor:ed with a key (99).
- When the code is to be executed it gets “decrypted”, executed, and re-encrypted.
- The green code would normally execute at obfuscation time.
- Every subsequent time the `modexp` routine gets called the pink code first decrypts the blue code, executes it, and then the yellow code re-encrypts it.

Practical issues

- Pages have to be modifiable and executable. (See next slide).
- You have to flush the CPU's data cache before executing new code you have generated. (Why?) X86 does this automatically.

```
void makeCodeWritable(caddr_t first, caddr_t last) {
   caddr_t firstpage =
      first - ((int)first % getpagesize());
   caddr_t lastpage =
      last - ((int)last % getpagesize());
   int pages=(lastpage-firstpage)/getpagesize()+1;
   if (mprotect(
         firstpage,
         pages*getpagesize(),
         PROT_READ|PROT_EXEC|PROT_WRITE
       )==-1)
          perror("mprotect");
}
```

Decrypting by Emulation

- “Encrypting” binaries is often re-invented!
- Attack: run the program inside an emulator that prints out every executed instruction.
- The instruction trace can be analyzed (re-rolling loops, removing decrypt-and-jump artifacts, etc.) and the original code recovered.

Replacing Instructions

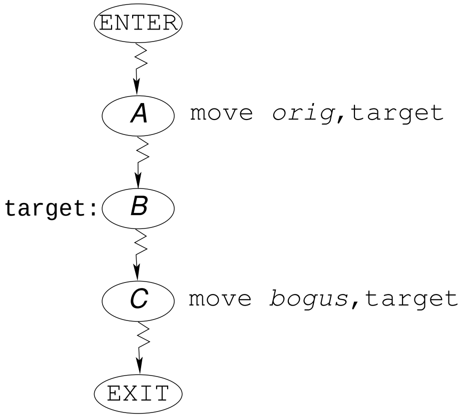
Kanzaki's Algorithm

- Motivation: make it hard for the adversary to snapshot the code.
- Idea: replace real instructions by bogus ones.
- Right before execution, the bogus instruction is replaced by the real one.
- Just after execution, the real instruction is replaced by the bogus one!

```
int player_main (int argc, char *argv[]) {
    char orig = (*(caddr_t)&&target);
    (*(caddr_t)&&target) = 0;

    ... ... ...

    for(i=0;i<len;i++) {
        (*(caddr_t)&&target) = orig;

        ... ... ...

        target:
        printf("%f\n",decoded);
        (*(caddr_t)&&target) = 0;
    }
}
int main (int argc, char *argv[]) {
    makeCodeWritable(...);
    player_main(argc,argv);
}
```

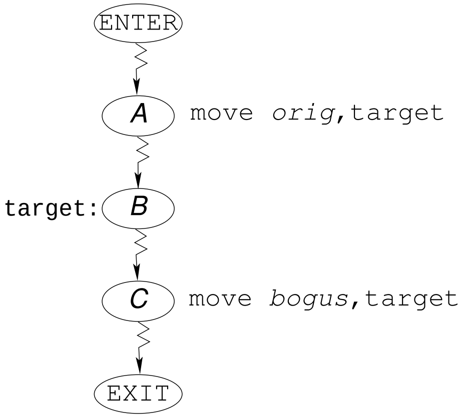
Algorithm Details

- Find three points *A*, *B*, *C* in the control flow graph:



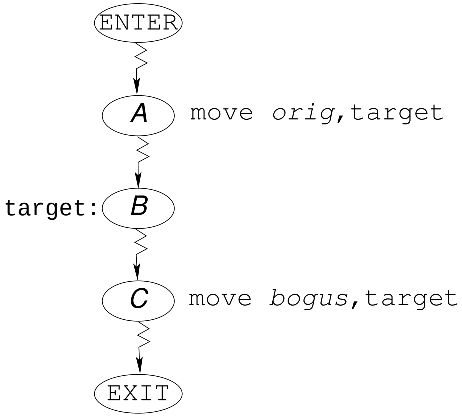
Algorithm Details

- Every path to *B* must flow through *A* and every path from *B* must flow through *C*:



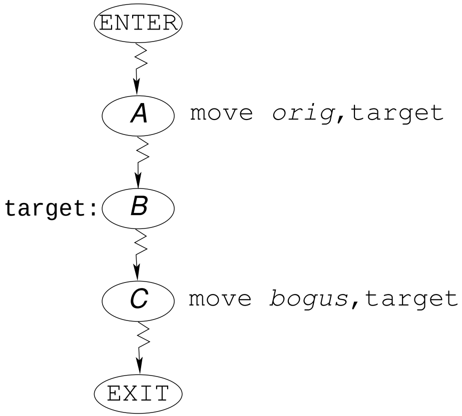
Algorithm Details

- At *A*: insert an instruction which overwrites the target instruction with its original value:



Algorithm Details

- At *C*: insert an instruction which overwrites the target with the bogus value:



Attack: set pages unwritable!

- The attacker calls `mprotect` to set the code region to readable and executable, but not writable. (See next slide).
- When the program tries to write into the code stream the operating system throws an exception.
- Under debugging, see where this happens!

```
(gdb) call (int)mprotect(0x2000,0x3000,5)
(gdb) cont
EXC_BAD_ACCESS, Could not access memory.
KERN_PROTECTION_FAILURE at address: 0x00002934
0x000028c0 in player_main
30            (*(caddr_t)&&target) = orig;
(gdb) x/i $pc
0x28c0 <player_main+220>:       stb     r0,0(r2)
(gdb) print (char)$r0
$7 = -64
(gdb) print/x (int)$r2
$10 = 0x2934
```

Code Merging

Madou’s Algorithm: Dynamic Code Merging

- Motivation: Keep the program in constant flux!

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- Motivation: Keep the program in constant flux!
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- Idea: Two or more functions *share* the same location in memory!
- Before *f* is called, patch memory to ensure *f* is loaded.

Example: Original Code

- Obfuscate a program that contains two functions f_1 and f_2:

f_1	
0	10
1	5
2	6
3	20
4	99

f_2	
0	10
1	9
2	3
3	20

- To the left is byte index in the function, to the right the code byte at the location.
- Note: At index 0, both f_1 and f_2 have the same code byte (10).

Example: Obfuscation Time

- During obfuscation replace f_1 and f_2 with the template T and two edit scripts e_1 and e_2:

T

0	10
1	?
2	?
3	20
4	99

$$\begin{aligned} e_1 &= [1 \to 5, 2 \to 6] \\ e_2 &= [1 \to 9, 2 \to 3] \end{aligned}$$

Example: Calling $f_1()$ at Run Time

- Program calls $f_1()$: patch T using e_1.
- Replace the code-byte at offset 1 with 5 and the code-byte at offset 2 with 6.

T

0	10
1	?
2	?
3	20
4	99

$$\begin{aligned} e_1 &= [1 \rightarrow 5, 2 \rightarrow 6] \\ e_2 &= [1 \rightarrow 9, 2 \rightarrow 3] \end{aligned}$$

Example: Calling $f_1()$ at Run Time

- If you call f_1 again (without intervening calls to f_2), no need to patch!!!

T

0	10
1	?
2	?
3	20
4	99

$$\begin{aligned} e_1 &= [1 \to 5, 2 \to 6] \\ e_2 &= [1 \to 9, 2 \to 3] \end{aligned}$$

Example: Calling $f_2()$ at Run Time

- If you call f_1 again (without intervening calls to f_2), no need to patch!!!
- Program calls $f_2()$: patch T using e_2.
- T memory region will constantly change, first containing an incomplete function and then alternating between containing the code-bytes for f_1 and f_2.

Algorithm step 1: Clustering

- Decide which functions should be in the same *cluster*, i.e. reside in the same template at runtime.

Algorithm step 1: Clustering…

- Avoid putting f_1 and f_2 in the same cluster if they are called like this:

```
while(1) {
    f1();
    f2();
}
```

Algorithm step 2: Make scripts and patch routine

- Create a template T_k containing the intersection of the code-bytes of the functions in c_k.
- For each function f_i in c_k create an edit script e_i such that applying e_i to the code-bytes of T_k creates the code-bytes of f_i.

Dynamic Code Merging

- Original code:

```
int val = 0;
void f1(int* v) {*v=99;}
void f2(int* v) {*v=42;}
int main (int argc, char *argv[]) {
   f1(&val);
   f2(&val);
}
```

```
EDIT script1[200], script2[200];
char* template;
int template_len, script_len = 0;
typedef void(*FUN)(int*);
int val, state = 0;

void f1_stub() {
   if (state != 1) {
      patch(script1,script_len,template); state = 1;}
   ((FUN)template)(&val);
}
void f2_stub() {
   if (state != 2) {
      patch(script2,script_len,template); state = 2;}
   ((FUN)template)(&val);
}
int main (int argc, char *argv[]) {
   f1_stub(); f2_stub();
}
```

Attacks

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  1. Analyze binary, find `patch` routine an scripts.
  2. Running each call to `patch`(T_k, e_i) to recover the code!

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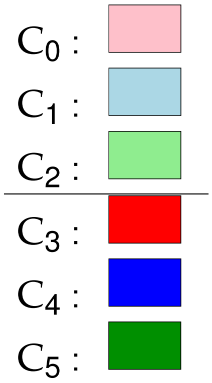
- Counterattack: Encrypt the scripts.

Attacks

- Note: the `patch` routine is in the clear!
- Note: the *scripts* are in the clear!
- Static attack:
  1. Analyze binary, find `patch` routine an scripts.
  2. Running each call to `patch`(T_k, e_i) to recover the code!
- Counterattack: Encrypt the scripts.
- Counter-counterattack: Intercept the decrypted scripts at runtime.

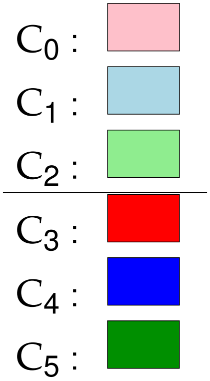
Self-Modifying State Machine

Aucsmith's algorithm



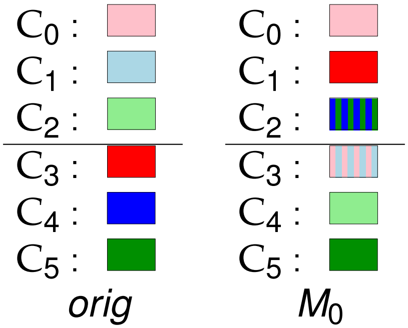
- A function is split into cells.

Aucsmith's algorithm

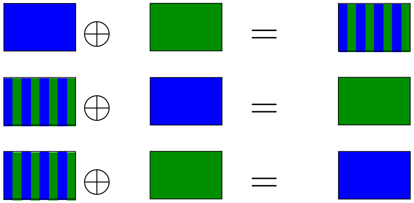


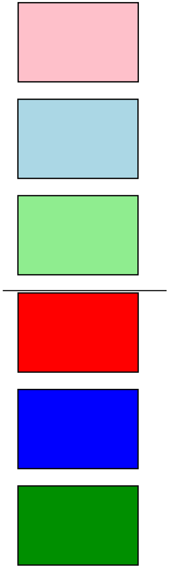
- A function is split into cells.
- The cells are divided into two regions in memory, upper and lower.

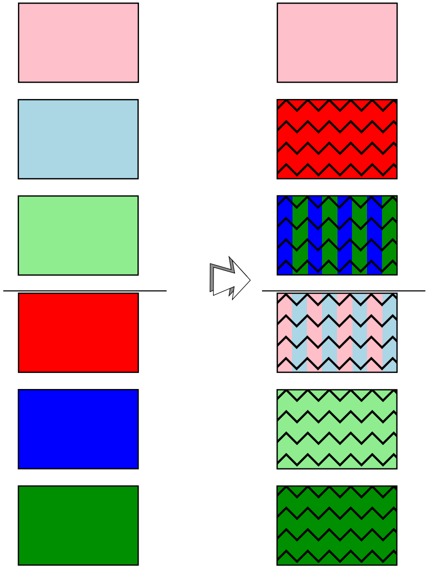
One step

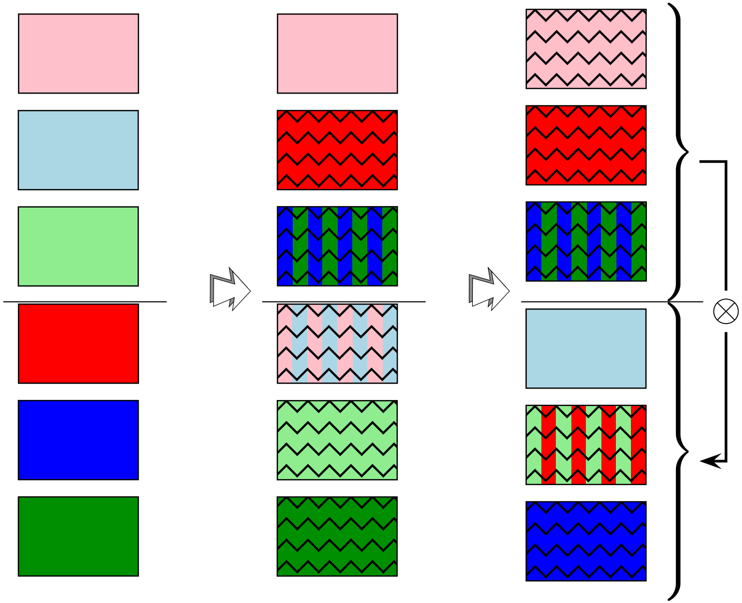


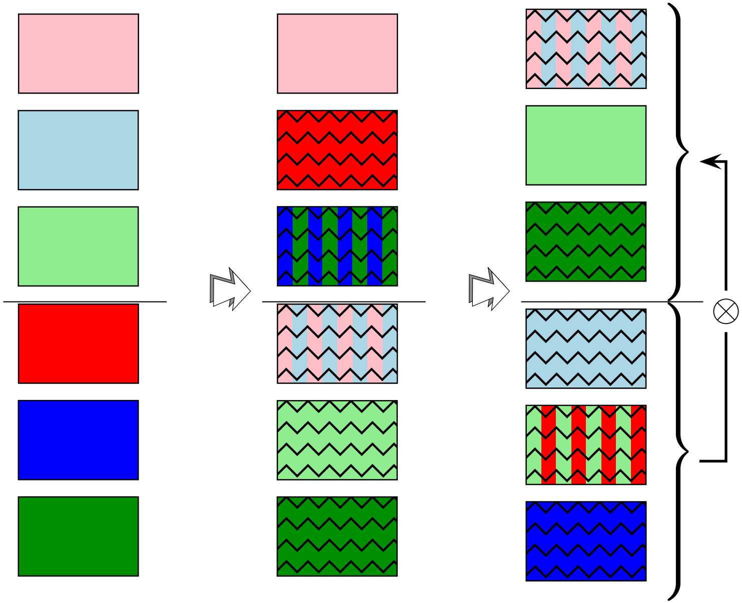
XOR!

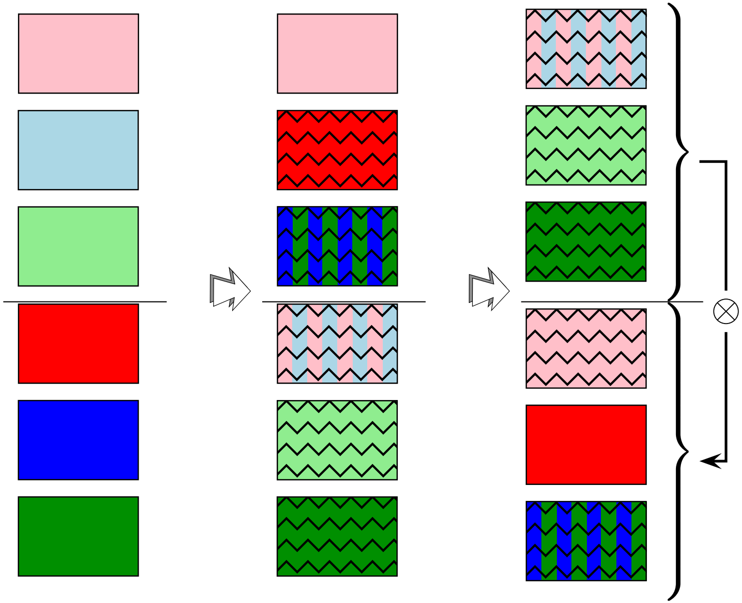


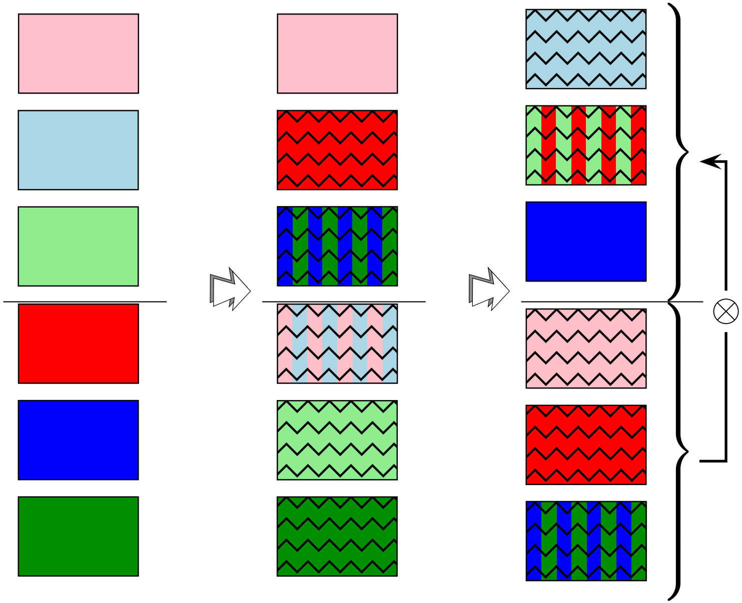


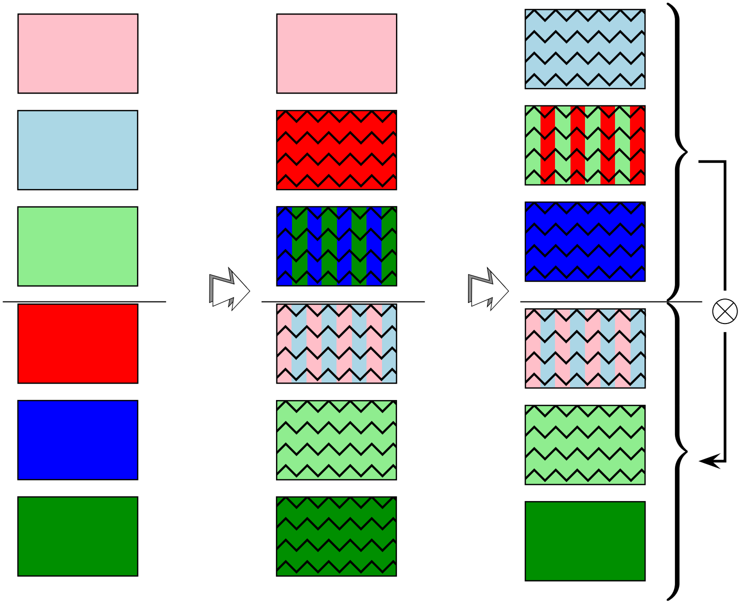


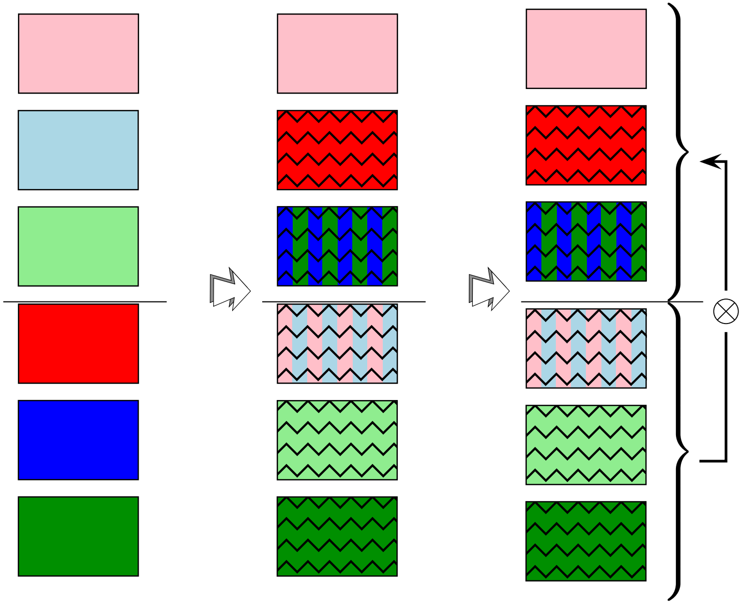




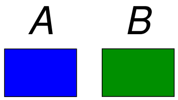








Why does this work?



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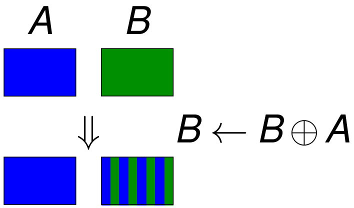

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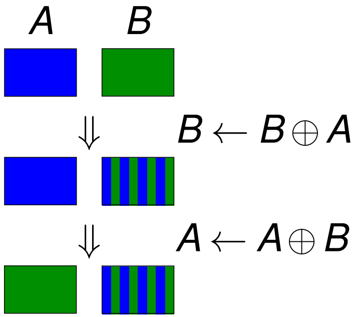

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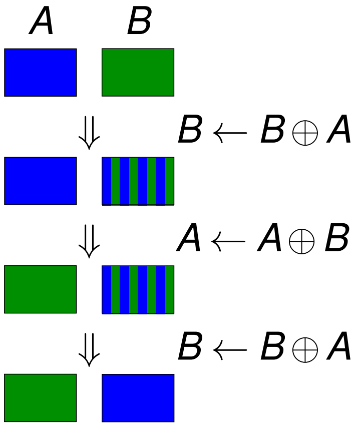
A
B
$B \leftarrow B \oplus A$
$A \leftarrow A \oplus B$
$B \leftarrow B \oplus A$

Runtime Encryption

Code as key material

- Encrypt the code to keep as little code as possible in the clear at any point in time during execution.

Code as key material

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- Encrypt the code to keep as little code as possible in the clear at any point in time during execution.
- Extremes:
  1. Decrypt the next instruction, execute it, re-encrypt it, . . . $\Rightarrow$ only one instruction is ever in the clear!
  2. Decrypt the entire program once, prior to execution, and leave it in cleartext. $\Rightarrow$ easy for the adversary to capture the code.

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- $\Rightarrow$ At most two functions are ever in the clear!

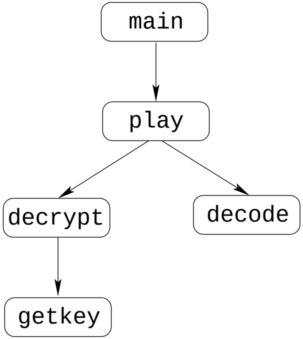
Code as key material

- What do we use as key? The code itself!

Code as key material

- What do we use as key? The code itself!
- What cipher do we use?
  Something simple!

- Simple case: tree-shaped call-graph:



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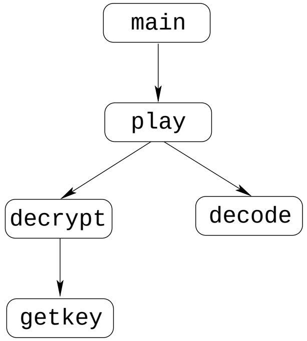

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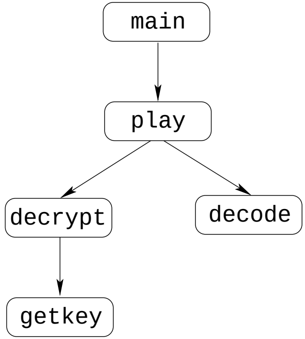

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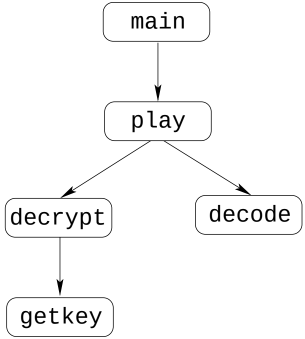

- Before/after procedure call: call guard function to decrypt/re-encrypt the callee.
- Entry/exit of the callee: encrypt/decrypt the caller.
- Key: Hash of the cleartext of the caller/callee.

```
int player_main (int argc, char *argv[]) {
   int user_key = 0xca7ca115;
   int digital_media[] = {10,102};
   guard(play,playSIZE,player_main,player_mainSIZE);
   play(user_key,digital_media,2);
   guard(play,playSIZE,player_main,player_mainSIZE);
}
int getkey(int user_key) {
   guard(decrypt,decryptSIZE,getkey,getkeySIZE);
   int player_key = 0xbabeca75;
   int v = user_key ^ player_key;
   guard(decrypt,decryptSIZE,getkey,getkeySIZE);
   return v;
}
int decrypt(int user_key, int media) {
   guard(play,playSIZE,decrypt,decryptSIZE);
   guard(getkey,getkeySIZE,decrypt,decryptSIZE);
   int key = getkey(user_key);
   guard(getkey,getkeySIZE,decrypt,decryptSIZE);
   int v = media ^ key;
   guard(play,playSIZE,decrypt,decryptSIZE);
   return v;
```

```
float decode (int digital) {
    guard(play,playSIZE,decode,decodeSIZE);
    float v = (float)digital;
    guard(play,playSIZE,decode,decodeSIZE);
    return v;
}
void play(int user_key, int digital_media[], int len) {
    int i;
    guard(player_main,player_mainSIZE,play,playSIZE);
    for(i=0;i<len;i++) {
        guard(decrypt,decryptSIZE,play,playSIZE);
        int digital = decrypt(user_key,digital_media[i]);
        guard(decrypt,decryptSIZE,play,playSIZE);

        guard(decode,decodeSIZE,play,playSIZE);
        printf("%f\n",decode(digital));
        guard(decode,decodeSIZE,play,playSIZE);
    }
    guard(player_main,player_mainSIZE,play,playSIZE);
}
```

```
void crypto (waddr_t proc,uint32 key,int words) {
   int i;
   for(i=1; i<words; i++) {
      *proc ^= key;
      proc++;
   }
}

void guard (waddr_t proc,int proc_words,
            waddr_t key_proc,int key_words) {
   uint32 key = hash1(key_proc,key_words);
   crypto(proc,key,proc_words);
}
```

Discussion

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- Integrity — make programs hard to understand to make them hard to change