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Ensure that a program executes as intended, even in the presence of an adversary who tries to disrupt, monitor, or change the execution.

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  1. makes tampering difficult
  2. <mark>detects</mark> when tampering has occured
  3. <mark>responds</mark> to the attack

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1. remove code from and/or insert new code into the executable file prior to execution;
2. remove code from and/or insert new code into the running program;
3. affect the runtime behavior of the program through external agents such as emulators, debuggers, or a hostile operating system.

Algorithms

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Algorithms

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2. various kinds of **response mechanisms**.
3. **oblivious hashing** algorithms which examine the *state* of the program for signs of tampering.
4. **remote software authentication** — determine that a program running on a remote machine has not been tampered with (WoW problem).

Outline
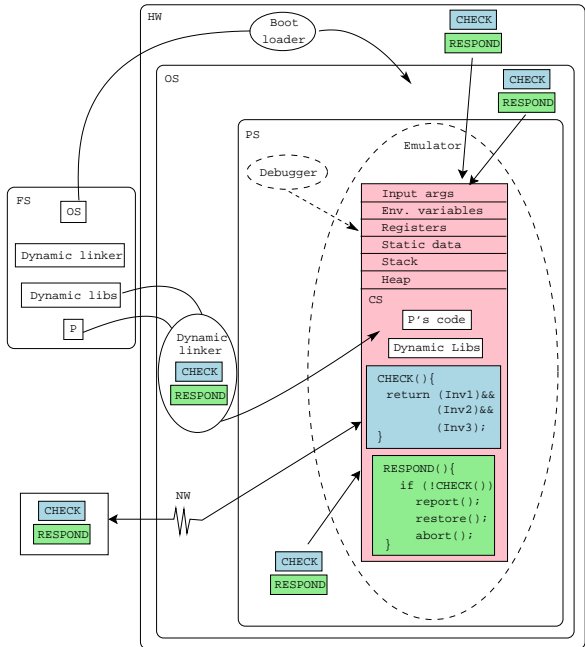
1. **Modify files:**
   - P's executable file
   - dynamic linker
   - dynamic libraries

How does the adversary attack P?

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2. Modify the operating system
3. Run P under emulation
4. Modify P while running under debugging

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What do we want?

Ensure P is healthy and the environment isn't hostile:

1. Unadulterated hardware and operating system
2. Unmodified P's code
3. Not running under emulation
4. Not being modified by a debugger
5. The right dynamic libraries have been loaded

Checking for tampering — code checking

- Check that P's code hashes to a known value:

```
if (hash(P's code) != 0xca7ca115)
    return false;
```

Checking for tampering — result checking

- Instead of checking that the code is correct, CHECK can test that the *result* of a computation is correct.

```
quickSort(A,n);
for (i=0;i<(n-1);i++)
    if (A[i]>A[i+1])
        return false;
```

- "Am I being run under emulation?'

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Checking for tampering — environment checking

- "Am I being run under emulation?'
- "Is there a debugger attached to my process?"
- "Is the operating system at the proper patch level?"

Environment checking — Checking for debugging

```
#include <stdio.h>
#include <sys/ptrace.h>
int main() {
    if (ptrace(PTRACE_TRACEME))
        printf("I'm being traced!\n");
}
```

If you fail, you can assume you've been attached to a debugger:

```
> gcc -g -o traced traced.c
> traced
> gdb traced
(gdb) run
I'm being traced!
```

Environment checking — Checking for debugging

```c
#include <stdio.h>
#include <stdint.h>
#include <signal.h>
#include <unistd.h>
#include <setjmp.h>

jmp_buf env;

void handler(int signal) {
    longjmp(env,1);
}
```

```
int main() {
    signal(SIGFPE, handler);
    uint32_t start,stop;
    int x = 0;
    if (setjmp(env) == 0) {
        asm volatile (
            "cpuid\n"
            "rdtsc\n" : "=a" (start)
        );
        x = x/x;
    } else {
        asm volatile (
            "cpuid\n"
            "rdtsc\n" : "=a" (stop)
        );
        uint32_t elapsed = stop - start;
        if (elapsed >40000) printf("Debugged!\n");
        else                printf("Not debugged!\n");
    }
}
```

Environment checking — Checking for debugging

Here's the output when first run normally and then under a
debugger:

```
> gcc -o cycles cycles.c
> cycles
elapsed 31528: Not debugged!
> gdb cycles
(gdb) handle SIGFPE noprint nostop
(gdb) run
elapsed 79272: Debugged!
```

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4. **Degrade** the performance of the program.
5. **Report the attack** for example by "phoning home".
6. **Punish** the attacker by destroying the program or objects in its environment:
   - *DisplayEater* deletes your home directory.
   - Destroy the computer by repeatedly flashing the bootloader flash memory.

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Checking by introspection

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- We'll see a clever attack on all introspection algorithms!
- . . . And, We'll see a clever counter-attack!

Inserting Guards

```
          . . . . . . . . .
start  = start_address;
end    = end_address;
h = 0;
while (start < end) {
    h = h ⊕ *start;
    start++;
}
if (h != expected_value)
    abort();
goto *h;
          . . . . . . . . .
```

Attack model — Find the guards

1. Search for patterns in the static code, for example two code segment addresses followed by a test:

```
start = 0xbabebabe;
end   = 0xca75ca75;
while ( start < end ) {
```

2. Search for patterns in the execution, such as data reads into the code.

Attack model — Disable the guards

① Replace the if-statement by if (0)...:

```
if (0)
    abort ();
```

② Pre-compute the hash value and substitute it into the response code:

```
goto *expected_value;
```

Introspection 20/78

Tamperproofing Algorithm: Chang & Atallah

- Invented by two Purdue University researchers, Mike Atallah and Hoi Chang:

- Patented and with assistance from Purdue a start-up, Arxan, was spun off.

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- When a tampered function is found <mark>repair it</mark>!

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- Skype uses a similar technique.
- Multiple checkers can check the same region.
- Multiple responders can repair a tampered region.

```
int main (int argc, char *argv[]) {
   int user_key = 0xca7ca115;
   int media[] = {10,102};
   play(user_key,media,2);
}
int getkey(int user_key) {
   int player_key = 0xbabeca75;
   return user_key ^ player_key;
}
int decrypt(int user_key, int media) {
   int key = getkey(user_key);
   return media ^ key;
}
float decode (int digital) {return (float)digital;}
void play(int user_key, int media[], int len) {
   int i;
   for(i=0;i<len;i++)
      printf("%f\n",decode(decrypt(user_key,media[i])));
}
```

```
#define getkeyHASH 0xce1d400a
#define getkeySIZE 14
uint32 getkeyCOPY[] =
    {0x83e58955,0x72b820ec,0xc7080486,...};

#define decryptHASH 0x3764e45c
#define decryptSIZE 16
uint32 decryptCOPY[] =
    {0x83e58955,0xaeb820ec,0xc7080486,...};

#define playHASH 0x4f4205a5
#define playSIZE 29
uint32 playCOPY[] =
    {0x83e58955,0xedb828ec,0xc7080486,...};
```

```
int main (int argc, char *argv[]) {


    A();
}

int A() {


    B();
}

int B() {
    ...
}
```

```
uint32 B_COPY[]={0x83e58955,0xaeb820ec,0xc7080486,...};

int main (int argc, char *argv[]) {



   A();
}

int A() {
   B_hash = hash(B);
   if (B_hash != 0x4f4205a5)
      memcpy(B,B_COPY);
   B();
}

int B() {
   ...
}
```

```
uint32 A_COPY[] ={0x83e58955,0x72b820ec,0xc7080486,...};
uint32 B_COPY[]={0x83e58955,0xaeb820ec,0xc7080486,...};

int main (int argc, char *argv[]) {
   A_hash = hash(A);
   if (A_hash != 0x105AB23F)
      memcpy(A,A_COPY);
   A();
}

int A() {
   B_hash = hash(B);
   if (B_hash != 0x4f4205a5)
      memcpy(B,B_COPY);
   B();
}

int B() {
   ...
}
```

```
uint32 getkeyCOPY []  ={0x83e58955 ,0x72b820ec ,0xc7080486 ,...};
uint32 decryptCOPY []={0x83e58955 ,0xaeb820ec ,0xc7080486 ,...};
uint32 playCOPY []    ={0x83e58955 ,0xedb828ec ,0xc7080486 ,...};
uint32 decryptVal ;

int main (int argc , char *argv []) {
    uint32 playVal = hash((waddr_t)play,29);
    int user_key = 0xca7ca115 ;
    decryptVal = hash((waddr_t)decrypt,16);
    int media [] = {10,102};
    if (playVal != 0x4f4205a5 )
        memcpy((waddr_t)play,playCOPY,29*sizeof(uint32));
    play(user_key ,media ,2);
}

int getkey (int user_key ) {
    decryptVal = hash((waddr_t)decrypt,16);
    int player_key = 0xbabeca75 ;
    return user_key ^ player_key ;
}
```

```
int decrypt(int user_key, int media) {
    uint32 getkeyVal = hash((waddr_t)getkey,14);
    if (getkeyVal != 0xce1d400a)
        memcpy((waddr_t)getkey,getkeyCOPY,14*sizeof(uint32));
    int key = getkey(user_key);
    return media ^ key;
}

float decode (int digital) {
    return (float)digital;
}
void play(int user_key, int media[], int len) {
    if (decryptVal != 0x3764e45c)
        memcpy((waddr_t)decrypt,decryptCOPY,16*sizeof(uint32));
    int i;
    for(i=0;i<len;i++)
        printf("%f\n",decode(decrypt(user_key,media[i])));
}
```
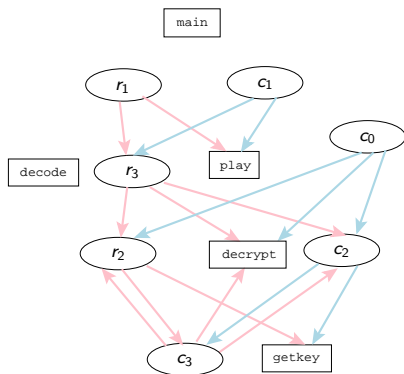
- code — code blocks
- c_i — checkers
- r_i — repairers

Here's the corresponding code, as it is laid out in memory:
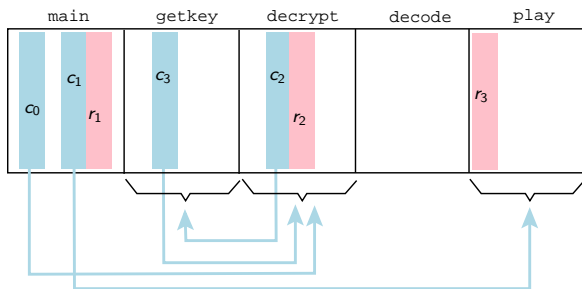
blue represent checkers, pink repairers.

Generating hash functions

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Generating hash functions

- Prevent collusive attacks $\Rightarrow$ generate a large number of different-looking hash functions.
- Self-collusive attacks = the adversary scans through the program for pieces of similar-looking code.
- No need to be "cryptographically secure".
- No need to generate a uniform distribution of values.
- Must be simple, fast, stealthy!

hash1

```
typedef unsigned int uint32;
typedef uint32* addr_t;

uint32 hash1 (addr_t addr,int words) {
    uint32 h = *addr;
    int i;
    for(i=1; i<words; i++) {
        addr++;
        h ^= *addr;
    }
    return h;
}
```

- Inline the function for better stealth.

hash2

```
uint32 hash2 (addr_t start, addr_t end) {
    uint32 h = *start;
    while (1) {
        start++;
        if (start >= end) return h;
        h ^= *start;
    }
}
```

- Will the compiler generate different code than for hash1???

hash3

```
int32 hash3 ( addr_t start , addr_t end , int step ) {
    uint32 h = * start ;
    while (1) {
        start += step ;
        if ( start >= end ) return h ;
        h ^= * start ;
    }
}
```

- Step through the code region in more or less detail $\Rightarrow$ balance performance and accuracy.

hash4

```
uint32 hash4 (addr_t start,addr_t end,uint32 rnd) {
    addr_t t = (addr_t)((uint32)start + (uint32)end + rnd);
    uint32 h = 0;
    do {
        h += *((addr_t)(-(uint32)end-(uint32)rnd+(uint32)t));
        t++;
    } while (t < (addr_t)((uint32)end+
                          (uint32)end+(uint32)rnd));
    return h;
}
```

- Scan backwards.
- Obfuscate to prevent pattern-matching attacks: add (and then subtract out) a random value (rnd).

hash5

```
uint32 hash5 ( addr_t start , addr_t end , uint32 C ) {
   uint32 h = 0;
   while ( start < end ) {
      h = C *(* start + h );
      start ++;
   }
   return h ;
}
```

- Generate 2,916,864 variants, each less than 50 bytes of x86, by reordering basic blocks, inverting conditional branches, replacing multiplication instructions by combinations of shifts, adds, and address computations, permuting instructions within blocks, permuting register assignments, and replacing instructions with equivalents.

Outline

The Skype obfuscated protocol

- Voice-over-IP service where users are charged for computer-to-phone and phone-to-computer calls.
- The Skype client is heavily tamperproofed and obfuscated.
- 2005: Skype was bought by eBay for $2.6 billion.
- 2006: Hacked by two researchers at the EADS Corporate Research Center in France.

- The client binary contains:
  1. hardcoded RSA keys
  2. the IP address and port number of a known server
- Break the protection and build your own VoIP network!

Skype protection: Stage 1
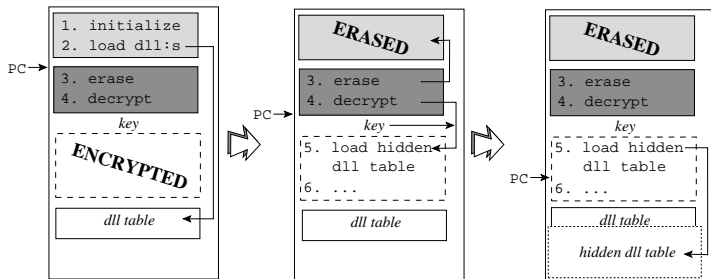
- pink: cleartext code, loads dlls.
- blue: erase pink code, decrypts green code.
- green: loads hidden dlls (yellow).
- Erasing and hiding dlls: hard to recreate binary.

Skype protection: Stage 2

- Check for debuggers:
  1. Signatures of known debuggers
  2. Timing tests

- Checker network:
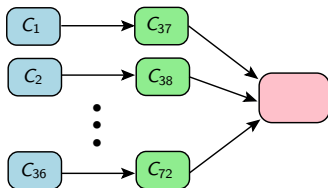
- Hash function computes the address of the next location to be executed!
- Hash functions are obfuscated, but not enough — attacked by pattern-matching.

```
uint32 hash7() {
   addr_t addr;
   addr = (addr_t)((uint32)addr^(uint32)addr);
   addr = (addr_t)((uint32)addr + 0x688E5C);
   uint32 hash = 0x320E83 ^ 0x1C4C4;
   int bound = hash + 0xFFCC5AFD;
   do {
      uint32 data = *((addr_t)((uint32)addr + 0x10));
      goto b1; asm volatile(".byte 0x19");
      b1: hash = hash ⊕ data;
      addr -= 1; bound--;
   } while (bound!=0);
   goto b2;
      asm volatile(".byte 0x73");
   b2:
   goto b3;
      asm volatile(".word 0xC8528417,0xD8FBBD1,0xA36CFB2F");
      asm volatile(".word 0xE8D6E4B7,0xC0B8797A");
      asm volatile(".byte 0x61,0xBD");
   b3:
   hash-=0x4C49F346;  return hash;
}
```

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- How to attack introspection algorithms?
  1. Analyze the code to locate the checkers, or
  2. Analyze the code to locate the responders, then
  3. Remove or disable them without destroying the rest of the program.
- Attack can just as well be external to the program!

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Algorithm ʀᴇWOS: Attacking self-hashing algorithms

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  1. as code (when it's being executed) and
  2. as data (when it's being hashed).

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  1. redirect reads of the code to the original, unmodified program (hash values will be computed as expected!)
  2. redirect execution of the code to the modified program (the modified code will get executed!)

ATTACK(P, K):

1. Copy program P to P_{orig}.

2. Modify P as desired to a hacked version P'.

3. Modify the operating system kernel K such that data reads are directed to P_{orig}, instruction reads to P'. $\square$

- Typical memory management system:

- On a TLB miss walk the page tables (slow), and update the TLB with the new virtual-to-physical address mapping.
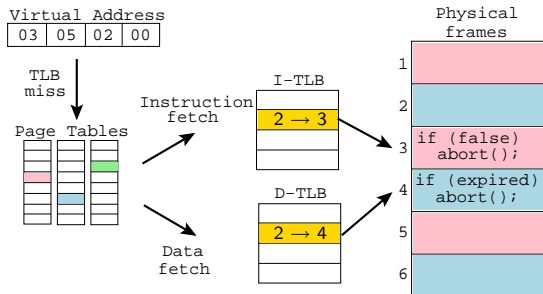
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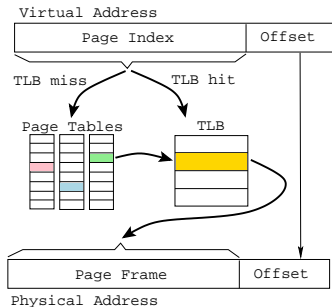
- On a TLB miss walk the page tables (slow), and update the TLB with the new virtual-to-physical address mapping.
- On the UltraSparc, the hardware gives the OS control on a TLB miss by throwing one of two exceptions depending on whether the miss was caused by a data or an instruction fetch
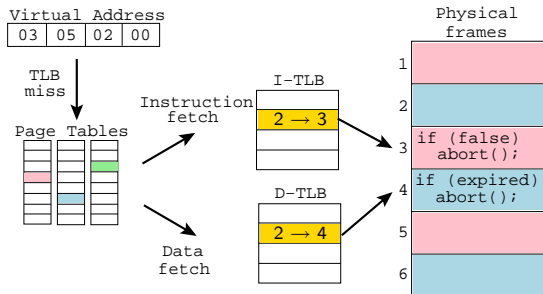
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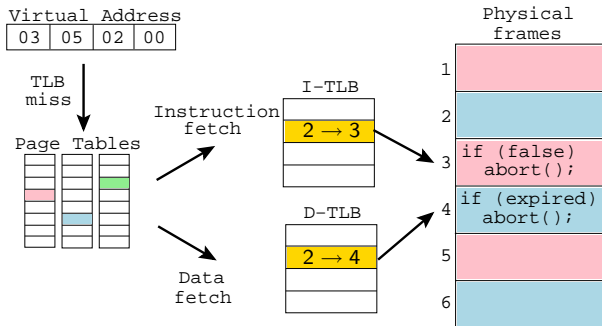
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2. Arrange the physical memory such that frame i comes from the hacked P and frame $i + 1$ is the corresponding original frame from P_{orig}.
3. Modify the kernel: if a page table lookup yields a $v \rightarrow p$ virtual-to-physical address mapping, I-TLB is updated with $v \rightarrow p$ and D-TLB with $v \rightarrow p + 1$.
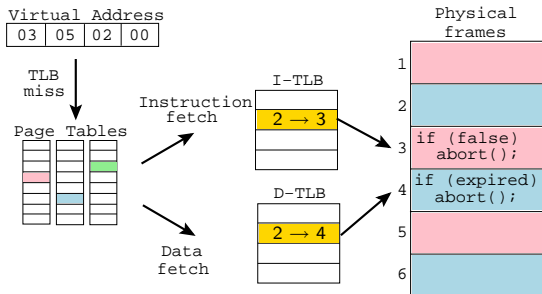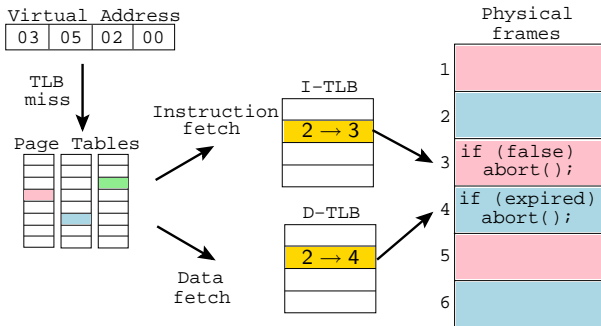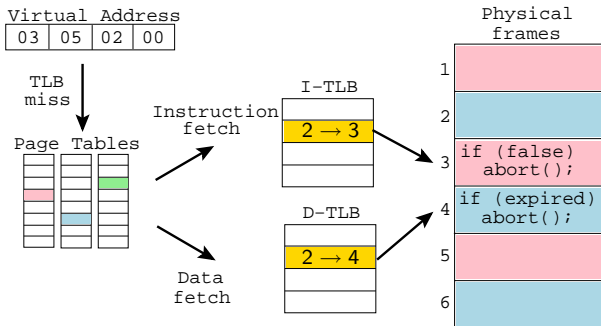
1. The attacker has modified the program to bypass a license-expired check.
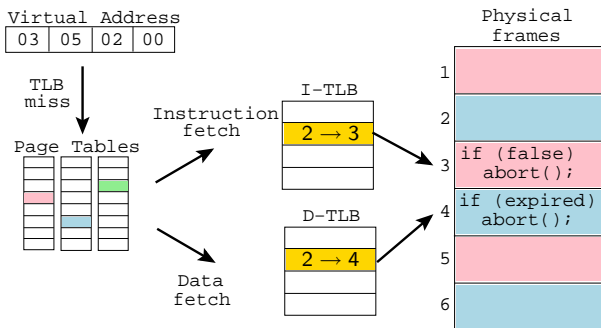
1. The attacker has modified the program to bypass a license-expired check.
2. The original program pages are in blue.

① The attacker has modified the program to bypass a license-expired check.

② The original program pages are in blue.

③ The modified program pages are in pink.

Algorithm REWOS: Attacking self-hashing algorithms

Virtual Address
| 03 | 05 | 02 | 00 |

TLB miss

Page Tables

Instruction fetch

I-TLB
$2 \rightarrow 3$

Data fetch

D-TLB
$2 \rightarrow 4$

Physical frames

1
2
3 if (false) abort();
4 if (expired) abort();
5
6

1. The program tries to **read** its own code in order to **execute** it ⇒ the processor throws an **I-TLB-miss** exception, the OS updates the I-TLB to refer to the modified page.

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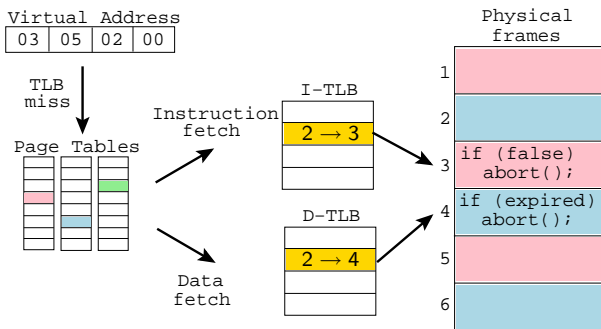
1. The program tries to **read** its own code in order to **execute** it
   ⇒ the processor throws an **I-TLB-miss** exception, the OS
   updates the I-TLB to refer to the modified page.
2. The program tries to read its own code in order to **hash** the
   processor throws a **D-TLB-miss** exception, and the OS
   updates the D-TLB to refer to the original, unmodified, page.

Outline

What's wrong with introspection algorithms?

- **Introspection algorithms**
    1. read their own code segment (unusual)!
    2. only check the validity of the code itself (not runtime data, function return values, . . .).

What's wrong with introspection algorithms?

- Introspection algorithms
  1. read their own code segment (unusual)!
  2. only check the validity of the code itself (not runtime data, function return values, . . .).
- Oblivious algorithms
  1. detect tampering from the *side-effects* the code produces
  2. check the correctess of data and control-flow

Oblivious $\Rightarrow$ the adversary should be unaware that his code is being checked.

Oblivious hashing

- More stealthy than introspection techniques.
  - We don't read our own code!
- An advanced form of <mark>assertion checking</mark>:

```
ASSERT x < 100;
ASSERT y != null;
```

- Works on Java as well as binary code.

Challenging functions

- Adding assertion checks automatically is hard!
  - How can we know what values variables should have???
- Instead, call functions with challenge inputs:

```
int  challenge  = 5;
int  expected   = 120;
int  result     = factorial(challenge);
if (result != expected)
    abort();
```

Challenging functions

- Be careful not to generate suspicious-looking hash values or challenge data:

```
if ( factorial (17) != 355687428096000)
    abort ();
```

- You can hide the hash value by making copies of every function:

```
int challenge = 17;
if ( factorial_orig ( challenge ) !=
    factorial_copy ( challenge ))
    abort ();
```

- IDEA: overlap basic blocks of x86 instructions.

# Algorithm TPJJV: Oblivious hashing

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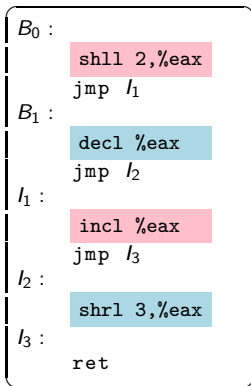
Algorithm TPJJV: Oblivious hashing

- IDEA: overlap basic blocks of x86 instructions.
- When one block executes it also computes a hash over the second block!
- The hash is computed *without* reading the code!
- Invulnerable to memory splitting attacks!
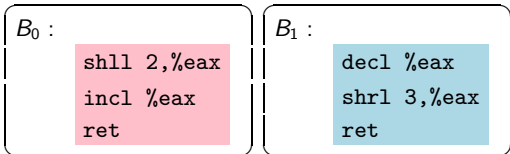
Merge the blocks by interleaving the instructions, inserting jumps to maintain semantics:

- The merged block has two entry points, B_0 and B_1.
- Want the two blocks also to *share instruction bytes*.
- Replace the jmp with xorl that takes a 4-byte literal argument:

```
B0 :
     shll 2,%eax
     xorl %ecx, next 4 bytes    // used to be jmp l1
B1 :
     decl %eax
     jmp  l2
     nop
     incl %eax
     ...
```

- The xorl instruction has, embedded in its immediate operand, the four bytes from decl; jmp; nop!

```
B₀
↓
shll $2,%eax    incl %eax    ret
⏝⏝⏝⏝⏝⏝⏝⏝       ⏝⏝⏝       ⏝⏝⏝
C1   E0   02        40         C3
0    1    2         3          4
```

```
B₁
↓
decl %eax    shrl $3,%eax    ret
⏝⏝⏝⏝         ⏝⏝⏝⏝⏝⏝⏝⏝       ⏝⏝⏝
48        C1   E8   03       C3
0         1    2    3        4
```
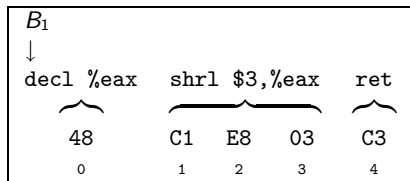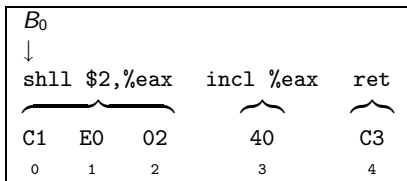
B_0
↓
shll $2,%eax   xorl $90E98148,%ecx   incl %eax

C1   E0   02   81   F1   48   81   E9   90   40   81   C1
 0   1   2   3   4   5   6   7   8   9   10   11

                        decl %eax   subl $C1814090,%ecx
                           ↑
                          B_1

                              addl $9003E8C1,%ecx   ret

                        81   C1   C1   E8   03   90   C3
                        10   11   12   13   14   15   16

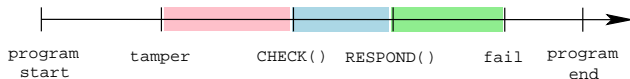   shrl $3,%eax   nop   ret

Algorithm TPJJV: Oblivious hashing

- Executing one block means also computing a hash over the other block into register %ecx!
- You can check the hash as usual.
- Clever use of the x86's architectural (mis-)features!
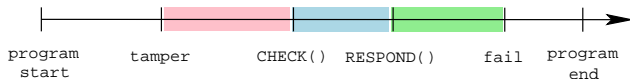- Overhead: up to 3x slowdown.

Outline

program   tamper   CHECK()   RESPOND()   fail   program
start   end
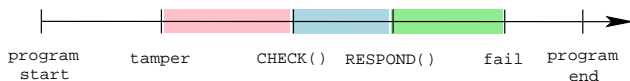
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Algorithm TPTCJ: Response Mechanisms

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Algorithm TPTCJ: Response Mechanisms

- CHECK checks for tampering,
- Later RESPOND takes action,
- Later still, the program actually fails

```
boolean tampered = false;
int global = 10;
          ...
if (hash(...)!=0xb1acca75) tampered = true;
          ...
if (tampered) global = 0;
          ...
printf("%i",10/global);
```

- RESPOND corrupts program state so that the actual failure follows much later

```
#include <time.h>
int global = 10;
          ...
if (time(0) % 2 == 0)
    printf("%i",10/global);
          ...
if (getpid() % 2 == 0)
    x = 5/global;
          ...
x = 3/global;
```

- Introduce a number of failure sites and probabilistically choose between them.
- Every time the attacker runs the hacked program it is likely to fail in one of the two green spots.

spatial separation: There should be as little static and dynamic
                     connection between the RESPOND site and the failure
                     site as possible.

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Algorithm TPTCJ: Response Mechanisms

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predictability: Once the tamper response has been invoked, the program should eventually fail.

- Think about legal implications of your tamper response mechanism!
- Don't deliberately destroy data...
- What if tamper-response was issued erroneously? ("I forgot my password, and after three tries the program destroyed my home directory!")
- Watch out for unintended consequences. (the program crashes with a file open...)

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Algorithm TPTCJ: Response Mechanisms

- RESPOND to set a global pointer variable to NULL, causing the program to crash when the pointer is later dereferenced.
- If the program doesn't have enough pointer variables TPTCJ creates new ones by adding a layer of indirection to non-pointer variables.
- Assumes that there are enough global variables to choose from.

```
int tampered=0;
int v;

void f() {
    v = 10;
}

void g() {
    f();
}

void h() {
}

int main() {
    if (...)
        tampered=1;
    h();
    g();
}
```

```
int tampered=0;
int v;
int *p_v = &v;

void f() {
    *p_v = 10;
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void g() {
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int tampered =0;
int v;
int *p_v = &v;

void f() {
   *p_v = 10;
}

void g() {
   f();
}

void h() {
   if (tampered)
       p_v = NULL;
}

int main() {
   if (...)
       tampered =1;
   h();
   g();
}
```

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2. To make the program crash you should set p_v to NULL. But where?
3. You want to avoid g and main since they will be on the call stack when f throws the *pointer-reference-to-nil* exception. (Check the stacktrace.)
4. Insert the failure-inducing code in h which is "many" calls away and not in the same call-chain as f.

Outline

Trustworthiness

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  - cannot modify P's environment!

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    - cannot modify P's environment!
- Essential for DRM, network gaming,...

Basic operations

- Check *P*'s environment:
  - Am I running under a debugger?
  - Am I running under emulation?
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- Check P's environment:
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  - Am I running under emulation?
  - Has the OS been hacked?
- Check P's code:
  - Have the executable bits been changed?
- Check P's dynamic data:
  - Is P in a legal executable state?

In practice. . .

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  - Check the code
  - Check the state

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- The response must be stealthy!
  - Simple attack: trace back from failure!

In practice. . .

- Use a combination of operations!
  - Check the environment
  - Check the code
  - Check the state
- You must check the checking code!
  - Simple attack: remove the checkers!
- The response must be stealthy!
  - Simple attack: trace back from failure!
- The detection must be stealthy!
  - Simple attack: detect reads of executable pages!