What is tamperproofing?

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

- A tamperproofing algorithm
  1. makes tampering difficult

What is tamperproofing?

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

- A tamperproofing algorithm
  1. makes tampering difficult
  2. detects when tampering has occured

What is tamperproofing?

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

- A tamperproofing algorithm
  1. makes tampering difficult
  2. detects when tampering has occured
  3. responds to the attack

What are typical attacks and defenses?

An attacker typically modifies the program with the intent to force it to chose a different execution path than the programmer intended:

1. remove code from and/or insert new code into the executable file prior to execution;

What are typical attacks and defenses?

An attacker typically modifies the program with the intent to force it to chose a different execution path than the programmer intended:

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;

What are typical attacks and defenses?

An attacker typically modifies the program with the intent to force it to chose a different execution path than the programmer intended:

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

1. introspection, i.e. tamperproofed programs which monitor their own code to detect modifications.

Algorithms

1. introspection, i.e. tamperproofed programs which monitor their own code to detect modifications.
2. various kinds of response mechanisms.

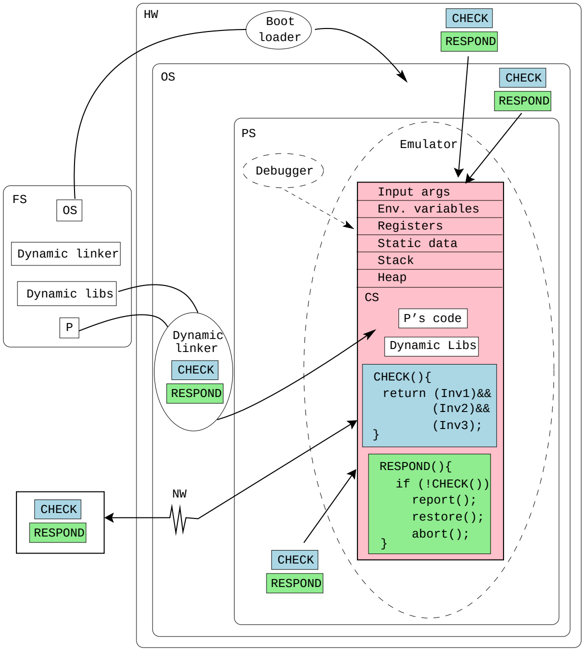
Algorithms

1. introspection, i.e. tamperproofed programs which monitor their own code to detect modifications.
2. various kinds of response mechanisms.
3. oblivious hashing algorithms which examine the *state* of the program for signs of tampering.

Algorithms

1. introspection, i.e. tamperproofed programs which monitor their own code to detect modifications.
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



```
CHECK(){
  return (Inv1)&&
         (Inv2)&&
         (Inv3);
}
```

```
RESPOND(){
   if (!CHECK())
      report();
      restore();
      abort();
}
```

How does the adversary attack P?

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

How does the adversary attack P?

1. Modify files:
    - P's executable file
    - dynamic linker
    - dynamic libraries
2. Modify the operating system

How does the adversary attack P?

1. Modify files:
   - P's executable file
   - dynamic linker
   - dynamic libraries
2. Modify the operating system
3. Run P under emulation

How does the adversary attack P?

1. Modify files:
   - P's executable file
   - dynamic linker
   - dynamic libraries
2. Modify the operating system
3. Run P under emulation
4. Modify P while running under debugging

What do we want?

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

1. Unadulterated hardware and operating system

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

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

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

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;
```

Checking for tampering — environment checking

- “Am I being run under emulation?’

Checking for tampering — environment checking

- “Am I being run under emulation?’
- “Is there a debugger attached to my process?”

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

```
#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!
```

How do we respond to tampering?

1. Terminate the program.

How do we respond to tampering?

1. Terminate the program.
2. Restore the program to its correct state, by patching the tampered code.

How do we respond to tampering?

1. Terminate the program.
2. Restore the program to its correct state, by patching the tampered code.
3. Deliberately return incorrect results, maybe deteriorate slowly over time.

How do we respond to tampering?

1. Terminate the program.
2. Restore the program to its correct state, by patching the tampered code.
3. Deliberately return incorrect results, maybe deteriorate slowly over time.
4. Degrade the performance of the program.

How do we respond to tampering?

1. Terminate the program.
2. Restore the program to its correct state, by patching the tampered code.
3. Deliberately return incorrect results, maybe deteriorate slowly over time.
4. Degrade the performance of the program.
5. Report the attack for example by “phoning home”.

How do we respond to tampering?

1. Terminate the program.
2. Restore the program to its correct state, by patching the tampered code.
3. Deliberately return incorrect results, maybe deteriorate slowly over time.
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.

Outline

Checking by introspection

- Augment the program with functions that compute a hash over a code region to compare to an expected value.

Checking by introspection

- Augment the program with functions that compute a hash over a code region to compare to an expected value.
- How can we be sure that the attacker won't tamper with the hash computation itself?

Checking by introspection

- Augment the program with functions that compute a hash over a code region to compare to an expected value.
- How can we be sure that the attacker won't tamper with the hash computation itself?
    1. build up a network of checkers and responders, so that checkers can check each other and responders can repair code that has been tampered with.

Checking by introspection

- Augment the program with functions that compute a hash over a code region to compare to an expected value.
- How can we be sure that the attacker won't tamper with the hash computation itself?
    1. build up a network of checkers and responders, so that checkers can check each other and responders can repair code that has been tampered with.
    2. hide the hash values so they won't give away the location of the checkers.

Checking by introspection

- Augment the program with functions that compute a hash over a code region to compare to an expected value.
- How can we be sure that the attacker won't tamper with the hash computation itself?
  1. build up a network of checkers and responders, so that checkers can check each other and responders can repair code that has been tampered with.
  2. hide the hash values so they won't give away the location of the checkers.
- We'll see a clever attack on all introspection algorithms!

Checking by introspection

- Augment the program with functions that compute a hash over a code region to compare to an expected value.
- How can we be sure that the attacker won't tamper with the hash computation itself?
    1. build up a network of checkers and responders, so that checkers can check each other and responders can repair code that has been tampered with.
    2. hide the hash values so they won't give away the location of the checkers.
- 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;
```

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.

Tamperproofing Algorithm: Chang & Atallah

- Checkers compute a hash over a region and compare to the expected value.

Tamperproofing Algorithm: Chang & Atallah

- Checkers compute a hash over a region and compare to the expected value.
- Checkers check the code and check each other as well!

Tamperproofing Algorithm: Chang & Atallah

- Checkers compute a hash over a region and compare to the expected value.
- Checkers check the code and check each other as well!
- Build up a network of code regions: blocks of user code, checkers, and responders.

Tamperproofing Algorithm: Chang & Atallah

- Checkers compute a hash over a region and compare to the expected value.
- Checkers check the code and check each other as well!
- Build up a network of code regions: blocks of user code, checkers, and responders.
- When a tampered function is found repair it!

Tamperproofing Algorithm: Chang & Atallah

- Checkers compute a hash over a region and compare to the expected value.
- Checkers check the code and check each other as well!
- Build up a network of code regions: blocks of user code, checkers, and responders.
- When a tampered function is found repair it!
- Skype uses a similar technique.
- Multiple checkers can check the same region.

Tamperproofing Algorithm: Chang & Atallah

- Checkers compute a hash over a region and compare to the expected value.
- Checkers check the code and check each other as well!
- Build up a network of code regions: blocks of user code, checkers, and responders.
- When a tampered function is found repair it!
- 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() {
   ...
}
```

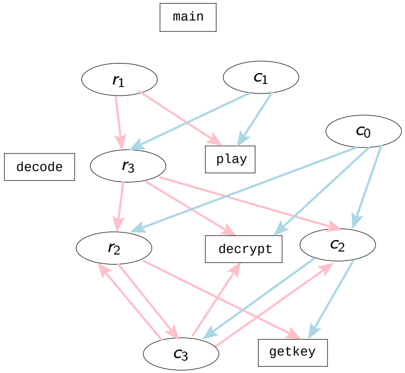
```
uint32 B_COPY[]={0x83e58955,0xaeb820ec,0xc7080486,...};

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])));
}
```

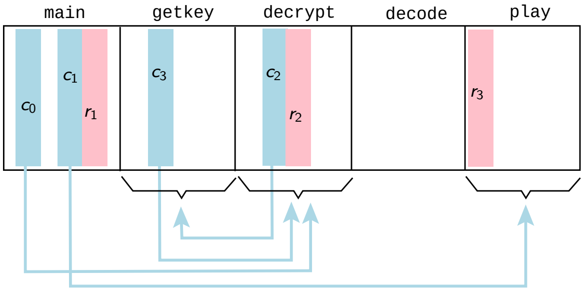
Algorithm Chang & Atallah: Checker network



- $\boxed{\text{code}}$ — code blocks
- c_i — checkers
- r_i — repairers

Algorithm TPCA: Checker Network

Here's the corresponding code, as it is laid out in memory:



blue represent checkers, pink repairers.

Generating hash functions

- Prevent collusive attacks $\Rightarrow$ generate a large number of different-looking hash functions.

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.

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".

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.

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

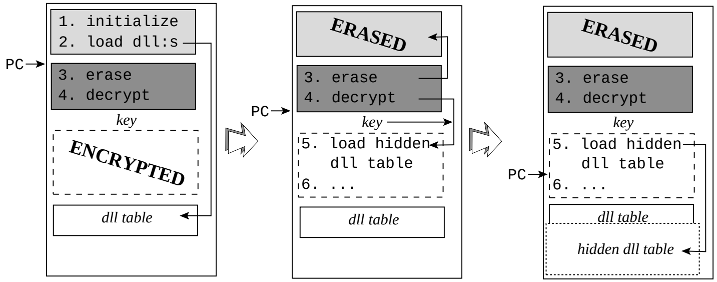
The Skype obfuscated protocol

- 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 Skype obfuscated protocol

- 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



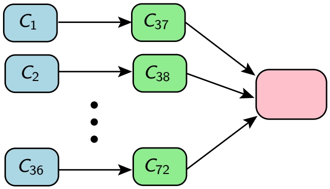
- pink: cleartext code, loads dlls.
- blue: erase pink code, decrypts green code.
- green: loads hidden dlls (yellow).
- Erasing and hiding dlls: hard to recreate binary.

Skype protection: Stage 2

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

Skype protection: Stage 3

- 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;
}
```

Outline

Algorithm reWOS: Attacking self-hashing algorithms

- How to attack introspection algorithms?
    1. Analyze the code to locate the checkers, or

Algorithm REWOS: Attacking self-hashing algorithms

- How to attack introspection algorithms?
  1. Analyze the code to locate the checkers, or
  2. Analyze the code to locate the responders, then

Algorithm REWOS: Attacking self-hashing algorithms

- 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.

Algorithm reWOS: Attacking self-hashing algorithms

- 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!

Algorithm REWOS: Attacking self-hashing algorithms

- Processors treat code and data differently.

Algorithm reWOS: Attacking self-hashing algorithms

- Processors treat code and data differently.
- TLBs (Translation Lookaside Buffers) and caches are split in separate parts for code and data.

Algorithm REWOS: Attacking self-hashing algorithms

- Processors treat code and data differently.
- TLBs (Translation Lookaside Buffers) and caches are split in separate parts for code and data.
- In the hash-based algorithms code is accessed
  1. as code (when it's being executed) and

$\Rightarrow$ sometimes a function will be read into the I-cache and sometimes into the D-cache.

Algorithm reWOS: Attacking self-hashing algorithms

- Processors treat code and data differently.
- TLBs (Translation Lookaside Buffers) and caches are split in separate parts for code and data.
- In the hash-based algorithms code is accessed
  1. as code (when it's being executed) and
  2. as data (when it's being hashed).

  $\Rightarrow$ sometimes a function will be read into the I-cache and sometimes into the D-cache.

Algorithm REWOS: Attacking self-hashing algorithms

- Attack: modify the OS such that
  1. redirect reads of the code to the original, unmodified program (hash values will be computed as expected!)

Algorithm reWOS: Attacking self-hashing algorithms

- Attack: modify the OS such that
    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!)

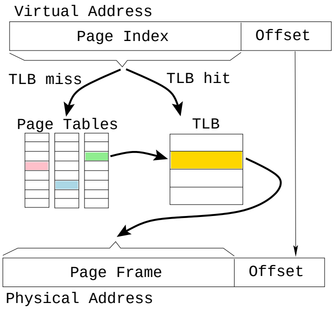
Algorithm reWOS: Attacking self-hashing algorithms

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'. □

Algorithm REWOS: Attacking self-hashing algorithms

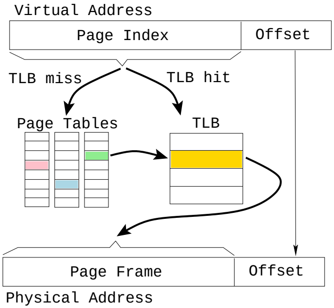
- Typical memory management system:



- On a TLB miss walk the page tables (slow), and update the TLB with the new virtual-to-physical address mapping.

Algorithm REWOS: Attacking self-hashing algorithms

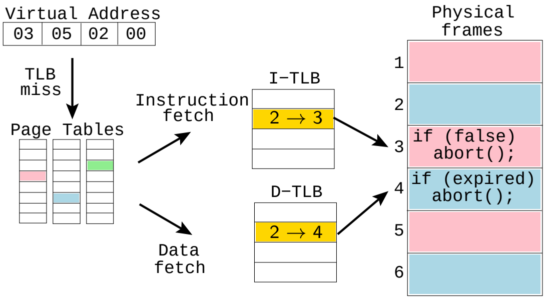
- Typical memory management system:



- On a TLB miss walk the page tables (slow), and update the TLB with the new virtual-to-physical address mapping.
- 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

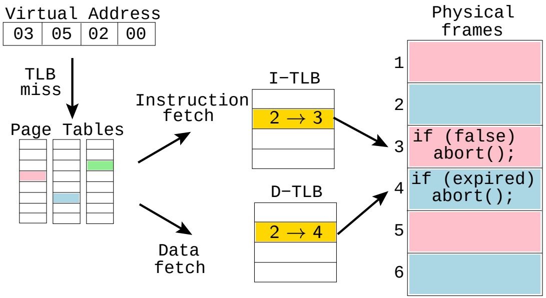
Algorithm reWOS: Attacking self-hashing algorithms

1. Copy P to P_{orig} and modify P however you like.



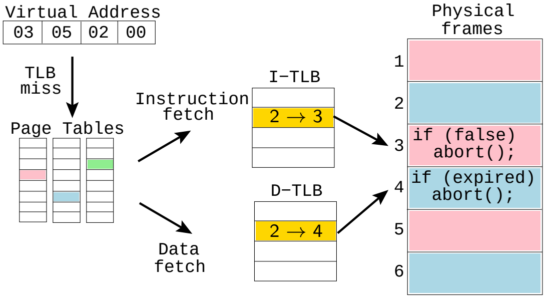
Algorithm REWOS: Attacking self-hashing algorithms

1. Copy P to P_{orig} and modify P however you like.
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}.

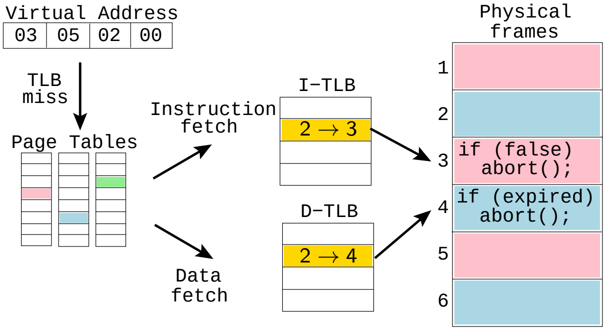


Algorithm reWOS: Attacking self-hashing algorithms

1. Copy P to P_{orig} and modify P however you like.
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 $v \rightarrow p+1$.

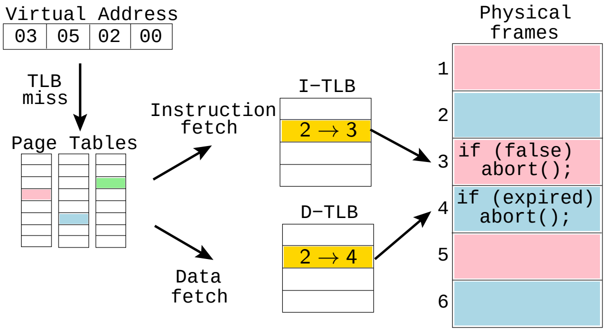


Algorithm REWOS: Attacking self-hashing algorithms



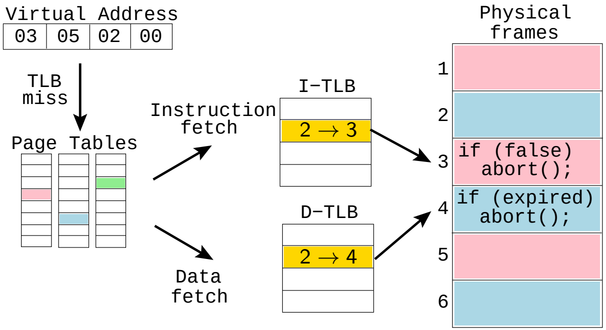
1. The attacker has modified the program to bypass a license-expired check.

Algorithm REWOS: Attacking self-hashing algorithms



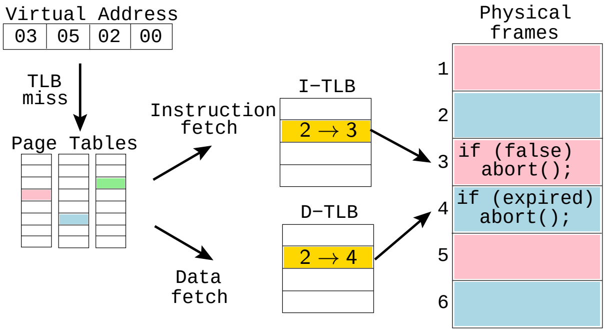
1. The attacker has modified the program to bypass a license-expired check.
2. The original program pages are in blue.

Algorithm reWOS: Attacking self-hashing algorithms



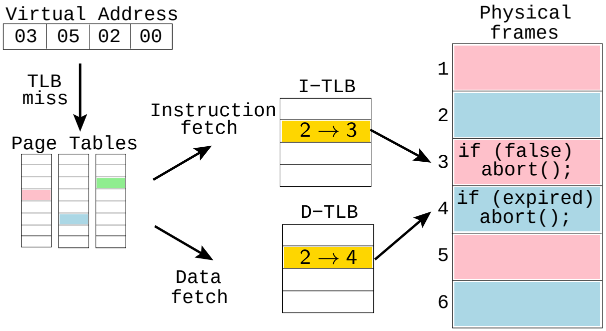
1. The attacker has modified the program to bypass a license-expired check.
2. The original program pages are in blue.
3. The modified program pages are in pink.

Algorithm REWOS: Attacking self-hashing algorithms



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.

Algorithm REWOS: Attacking self-hashing algorithms



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 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 assertion checking:

```
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();
```

Algorithm TPJJV: Oblivious hashing

- IDEA: overlap basic blocks of x86 instructions.

Algorithm tpJJV: Oblivious hashing

- IDEA: overlap basic blocks of x86 instructions.
- When one block executes it also computes a hash over the second block!

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!

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!

```
$B_0$ :
        shll 2,%eax
        incl %eax
        ret
```

```
$B_1$ :
        decl %eax
        shrl 3,%eax
        ret
```

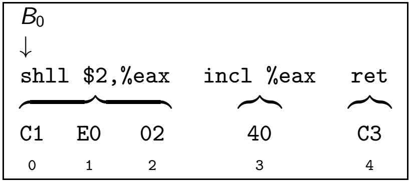
Merge the blocks by interleaving the instructions, inserting jumps to maintain semantics:

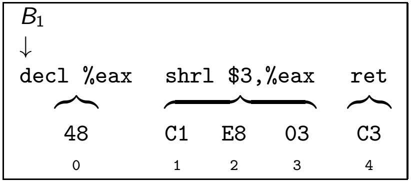
```
$B_0$ :
        shll 2,%eax
        jmp $l_1$
$B_1$ :
        decl %eax
        jmp $l_2$
$l_1$ :
        incl %eax
        jmp $l_3$
$l_2$ :
        shrl 3,%eax
$l_3$ :
        ret
```

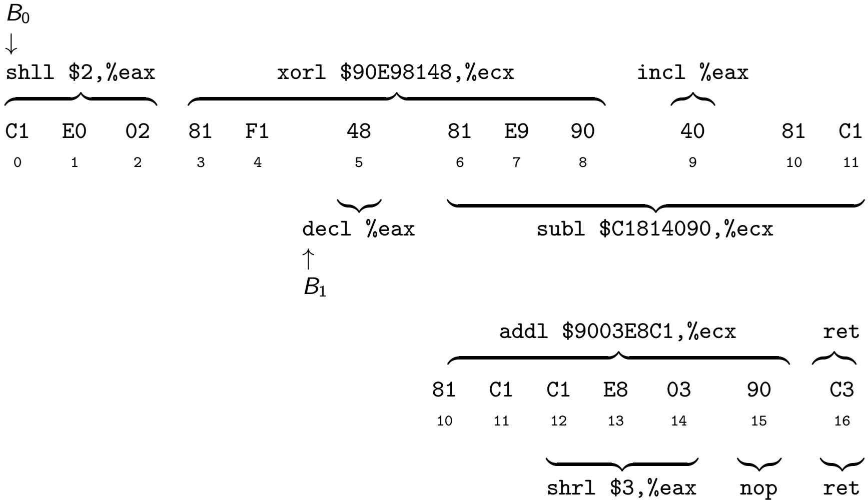
- The merged block has two entry points, B_0 and B_1.
- Want the two blocks also to *share instruction bytes*.
- Replace the `jmp` with `xorl` that takes a 4-byte literal argument:

```
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`!


B_0
↓
shll $2,%eax
incl %eax
ret
C1 E0 02
40
C3
0 1 2 3 4


B_1
↓
decl %eax
shrl $3,%eax
ret
48
C1 E8 03
C3
0 1 2 3 4

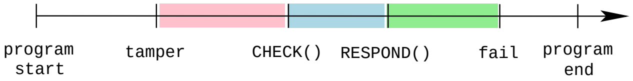

B_0
shll $2,%eax
xorl $90E98148,%ecx
incl %eax
C1 E0 02 81 F1 48 81 E9 90 40 81 C1
0 1 2 3 4 5 6 7 8 9 10 11
decl %eax
subl $C1814090,%ecx
B_1
addl $9003E8C1,%ecx
ret
81 C1 C1 E8 03 90 C3
10 11 12 13 14 15 16
shrl $3,%eax
nop
ret

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.

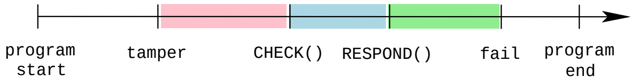
Outline

Algorithm TPTCJ: Response Mechanisms



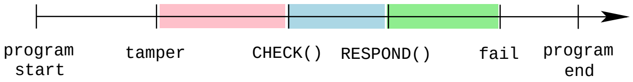
- `CHECK` checks for tampering,

Algorithm TPTCJ: Response Mechanisms



- `CHECK` checks for tampering,
- Later `RESPOND` takes action,

Algorithm TPTCJ: Response Mechanisms



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

Algorithm TPTCJ: Response Mechanisms

```
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

Algorithm TPTCJ: Response Mechanisms

```
#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.

Algorithm TPTCJ: Response Mechanisms

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

Algorithm TPTCJ: Response Mechanisms

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

temporal separation: A significant length of time should pass between the execution of `RESPOND` and the eventual failure.

Algorithm TPTCJ: Response Mechanisms

spatial separation:	There should be as little static and dynamic connection between the `RESPOND` site and the failure site as possible.
temporal separation:	A significant length of time should pass between the execution of `RESPOND` and the eventual failure.
stealth:	The test, response, and failure code you insert in the program should be stealthy

Algorithm TPTCJ: Response Mechanisms

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

temporal separation: A significant length of time should pass between the execution of RESPOND and the eventual failure.

stealth: The test, response, and failure code you insert in the program should be stealthy

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

Algorithm TPTCJ: Response Mechanisms

- 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. . .)

Algorithm TPTCJ: Response Mechanisms

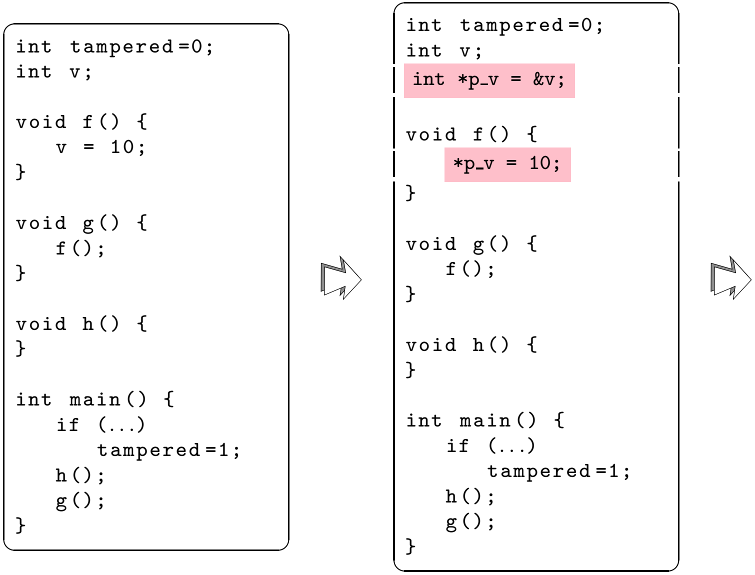
- `RESPOND` to set a global pointer variable to `NULL`, causing the program to crash when the pointer is later dereferenced.

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.

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;
}

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;
}

void g() {
   f();
}

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

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

Algorithm TPTCJ: Example

1. Create a global pointer variable `p_v`.

Algorithm TPTCJ: Example

1. Create a global pointer variable `p_v`.
2. To make the program crash you should set `p_v` to `NULL`. But where?

Algorithm TPTCJ: Example

1. Create a global pointer variable `p_v`.
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.)

Algorithm TPTCJ: Example

1. Create a global pointer variable `p_v`.
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

- Tamperproofing is about trustworthiness:
  - Can I trust my program when it's running on an untrusted site?

Trustworthiness

- Tamperproofing is about trustworthiness:
  - Can I trust my program when it's running on an untrusted site?
- For us to trust P, the adversary
  - cannot add/remove/change P's code!
  - cannot modify P's environment!

Trustworthiness

- Tamperproofing is about trustworthiness:
  - Can I trust my program when it's running on an untrusted site?
- For us to trust P, the adversary
  - cannot add/remove/change P's code!
  - 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?
    - Has the OS been hacked?

Basic operations

- Check P's environment:
    - Am I running under a debugger?
    - Am I running under emulation?
    - Has the OS been hacked?
- Check P's code:
    - Have the executable bits been changed?

Basic operations

- Check P's environment:
  - Am I running under a debugger?
  - 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. . .

- Use a combination of operations!
  - Check the environment
  - Check the code
  - Check the state

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!

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!

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!