ROPGuard: Runtime Prevention of Return-Oriented Programming Attacks

Ivan Fratrić
University of Zagreb
Faculty of Electrical Engineering and Computing

Zagreb, 24.09.2012

Overview

- Introduction
  - What is a memory corruption vulnerability?
  - Buffer overflow example
- Introduction to return-oriented programming (ROP)
- Related work
- ROPGuard
  - Main ideas
  - Selected Implementation details
  - Evaluation
- Conclusion and ideas for future work

Introduction

- Memory corruption vulnerability
  - contents of a memory location are unintentionally modified due to programming errors

CVE-2012-4969

Summary: Use-after-free vulnerability in the CMshtmlEd::Exec function in mshtml.dll in Microsoft Internet Explorer 6 through 9 allows remote attackers to execute arbitrary code via a crafted web site, as exploited in the wild in September 2012.

Published: 09/18/2012

CVSS Severity: 9.3 (HIGH)

CVE-2012-4166

Summary: Adobe Flash Player before 10.3.183.23 and 11.x before 11.4.402.265 on Windows and Mac OS X, before 10.3.183.23 and 11.x before 11.2.202.238 on Linux, before 11.1.111.16 on Android 2.x and 3.x, and before 11.1.115.17 on Android 4.x; Adobe AIR before 3.4.0.2540; and Adobe AIR SDK before 3.4.0.2540 allow attackers to execute arbitrary code or cause a denial of service (memory corruption) via unspecified vectors, a different vulnerability than CVE-2012-4163, CVE-2012-4164, and CVE-2012-4165.

Published: 08/21/2012

CVSS Severity: 10.0 (HIGH)

CVE-2012-2524

Summary: Microsoft Office 2007 SP2 and SP3 and 2010 SP1 allows remote attackers to execute arbitrary code or cause a denial of service (memory corruption) via a crafted Computer Graphics Metafile (CGM) file, aka "CGM File Format Memory Corruption Vulnerability."

Published: 08/15/2012

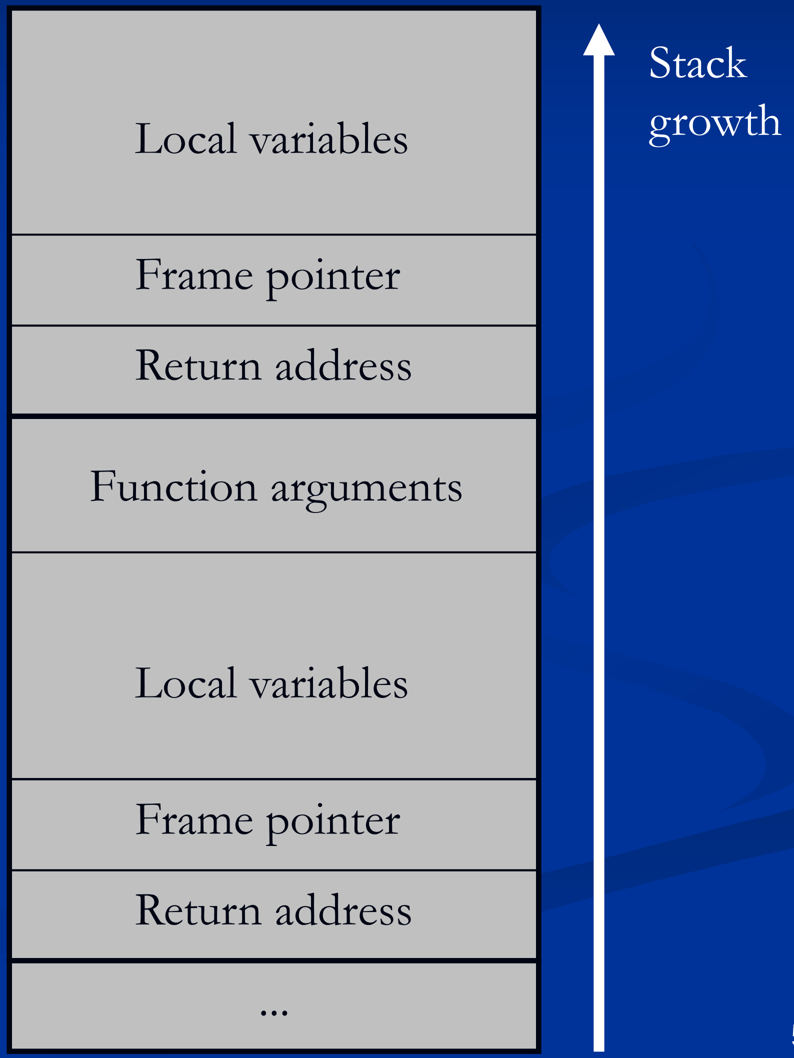
CVSS Severity: 9.3 (HIGH)

- In many cases memory corruption vulnerabilities can lead to arbitrary code execution

A long time ago ~~in a galaxy far, far away….~~

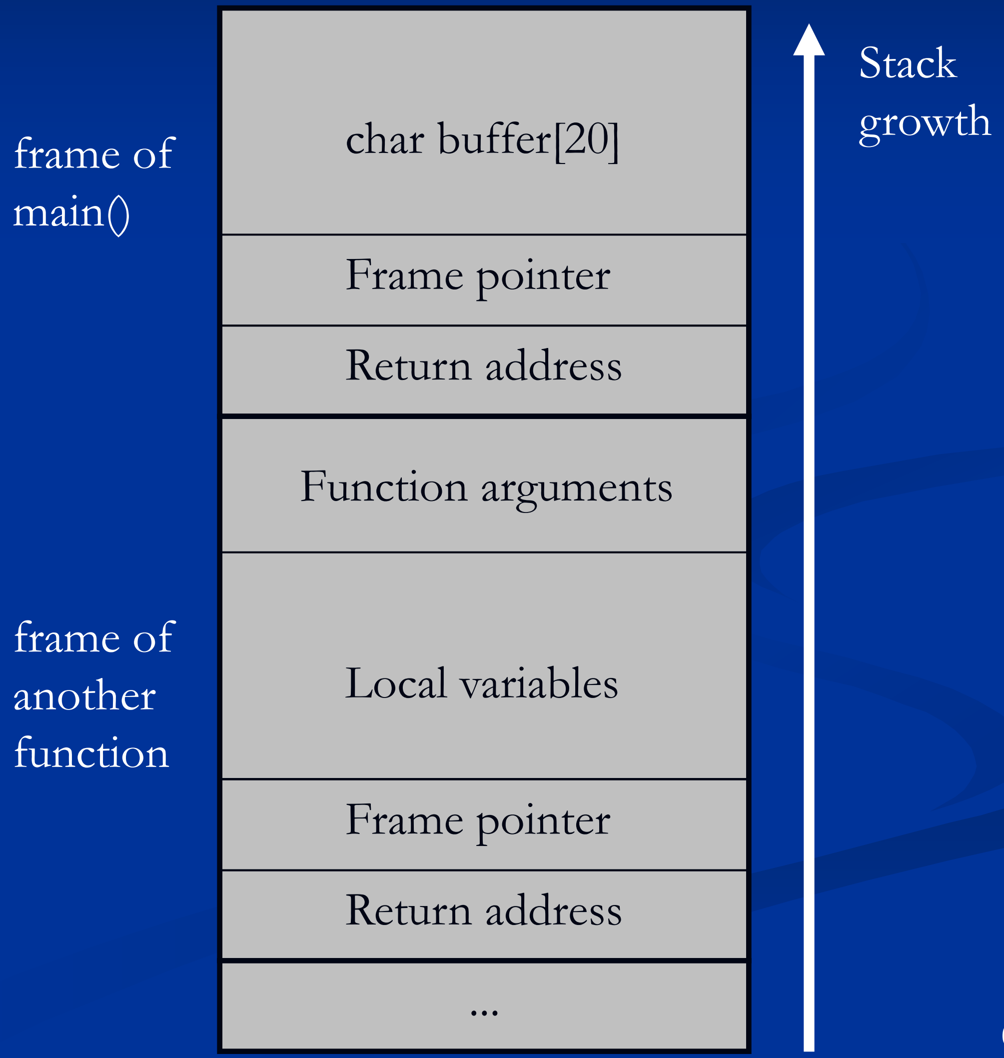
Example: Buffer overflow on stack

```c
#include <stdio.h>

void main()
{
    char buffer[20];
    gets(buffer);
    ...
}
```



Example: Buffer overflow on stack

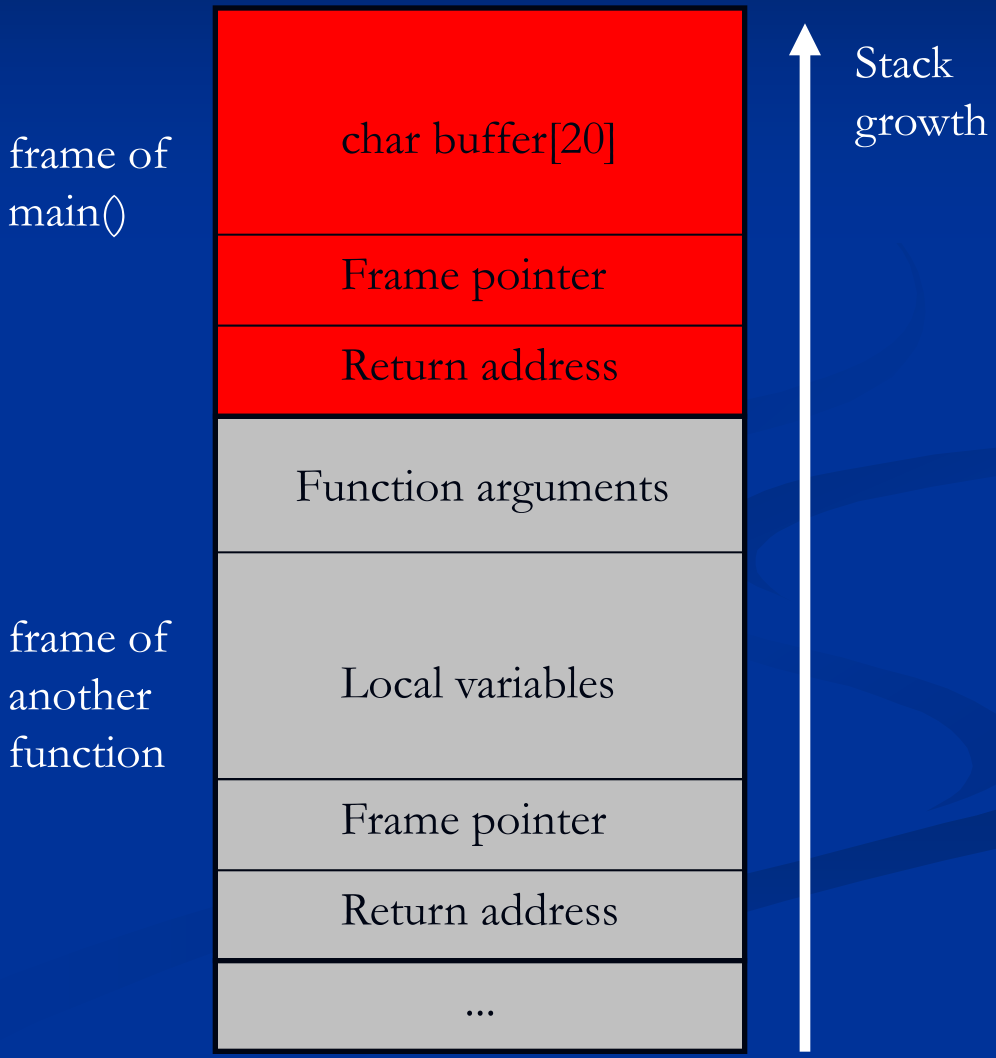
```c
#include <stdio.h>

void main()
{
    char buffer[20];
    gets(buffer);
    ...
}
```



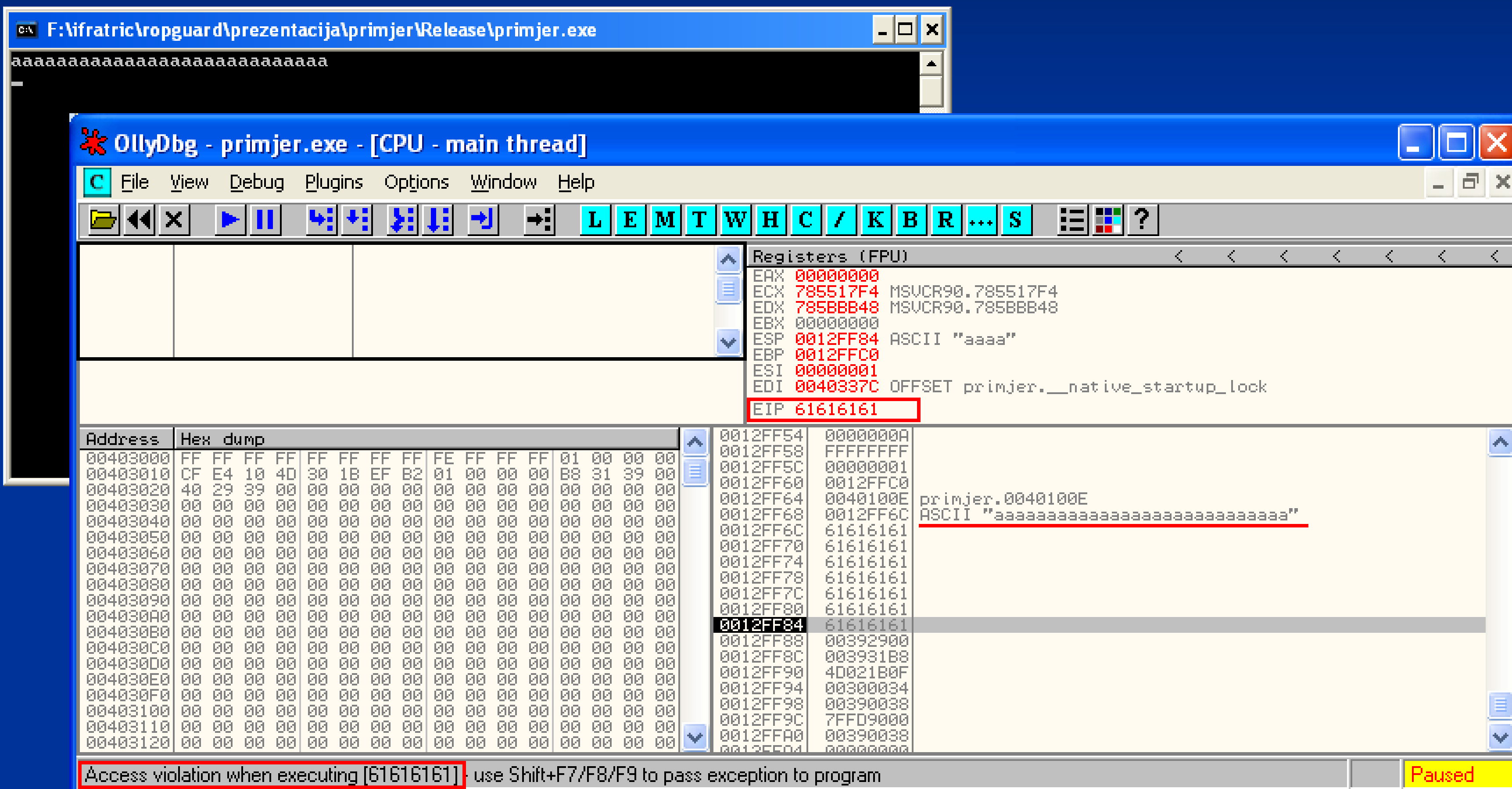
Example: Buffer overflow on stack

```
#include <stdio.h>

void main()
{
    char buffer[20];
    gets(buffer);
    ...
}
```

When main() returns, the attacker gains control over control flow (EIP)



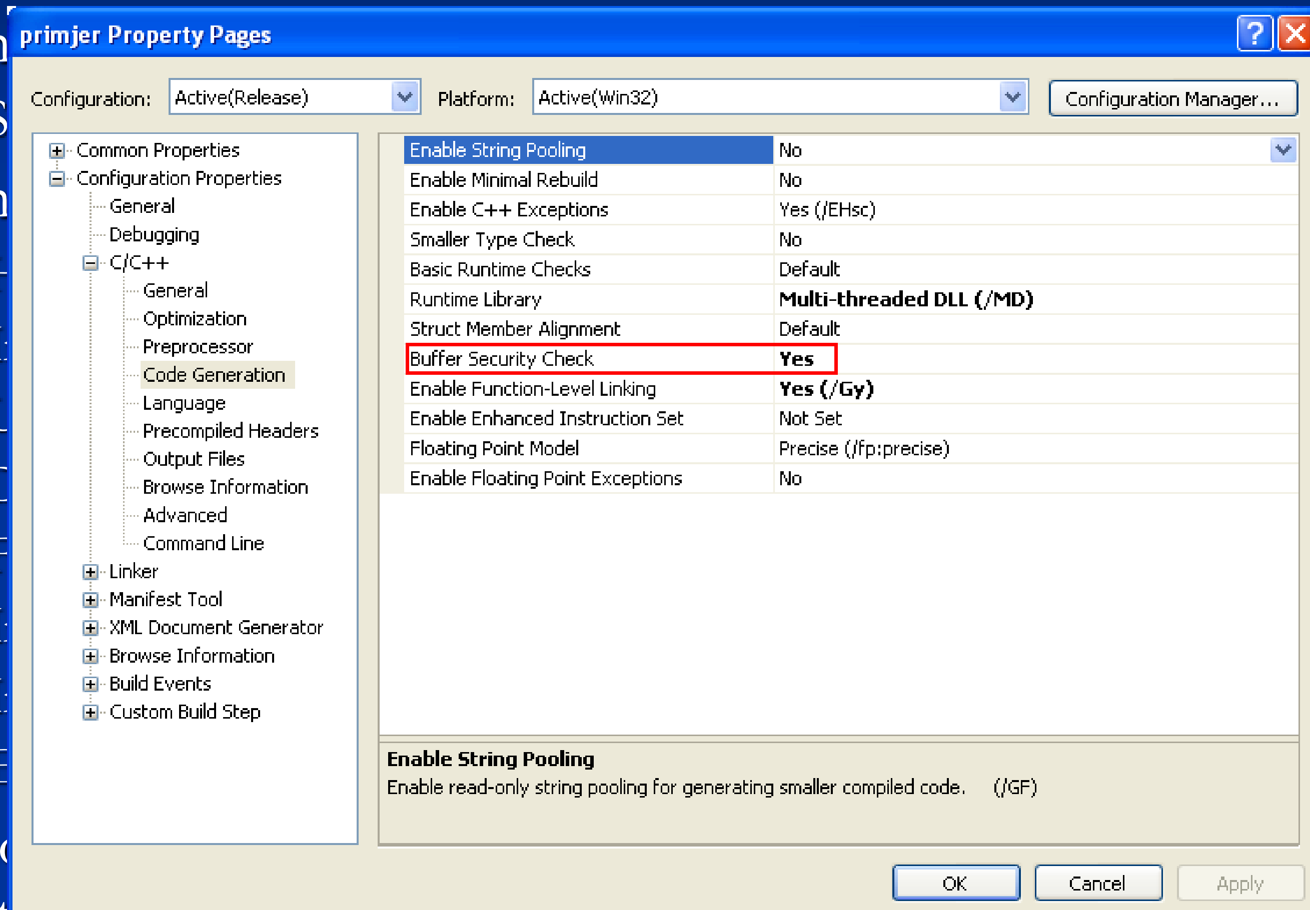
Example: Buffer overflow on stack



BACK TO THE FUTURE

Memory corruption vulnerabilities

- Man
  - S
- Man
  - H
  - I
  - U
  - D
  - F
  - I
  - I
  - E
- In c… te arbit… code



Data Execution Prevention (DEP)

- Hardware protection against exploitation
- A special flag (NX bit) indicates executable memory regions
  - Executable modules loaded in memory (.exe, .dll, etc.) are executable
  - Stack and heap are NOT executable
    - Can be made executable by calling special function i.e. VirtualProtect()
- Introduced on Linux in kernel 2.6.8, on Windows in Windows XP Service Pack 2

Return-oriented programming

- Generalization of return-to-libc and similar attacks
- Use small pieces of existing executable code to perform (complex) actions specified by the attacker
  - "small pieces of existing executable code" are called *gadgets*

Return-Oriented Programming

is a lot like a ransom note, but instead of cutting out letters from magazines, you are cutting out instructions from text segments

Return-oriented programming

- Gadget consists of two parts:
  - Instruction(s) that perform something useful
  - A part that transfers the code execution to the next gadget

- RETN instruction
  - Can be used to transfer execution to the next gadget *if* the attacker controls the stack

Return-oriented programming

- Simple example:
  - Attacker wants to write value 0x00001337 to address 0x12345678
- Break it into simple operations so that we can find appropriate gadgets in executable modules
  - Load 0x1337 into EAX
  - Load 0x12345678 into ECX
  - Do MOV [ECX],EAX

Return-oriented programming

- Simple example (cont.)
  - Attacker wants to write value 0x00001337 to address 0x12345678
- See if we have appropriate gadgets in executable code
- msvcr71.dll:

```
7C344CC1    58      POP EAX
7C344CC2    C3      RETN
```

```
7C3410C3    59      POP ECX
7C3410C4    C3      RETN
```

```
7C3503C8    8901    MOV DWORD PTR DS:[ECX],EAX
7C3503CA    C3      RETN
```

Return-oriented programming

- Simple example (cont.)
  - Attacker wants to write value 0x1337 to address 0x12345678
- Putting it all together

```
EAX: 00001337
ECX: 12345678
```

EIP →

```
????????    RETN
```

```
7C344CC1    POP EAX
7C344CC2    RETN
```

```
7C3410C3    POP ECX
7C3410C4    RETN
```

```
7C3503C8    MOV [ECX],EAX
7C3503CA    RETN
```

ESP →

0x7C344CC1
0x00001337
0x7C3410C3
0x12345678
0x7C3503C8
0x????????

Return-oriented programming

- Real-world example

```
0x7c37653d, # POP EAX # POP EDI # POP ESI # POP EBX # POP EBP # RETN
0xfffffdff, # Value to negate, will become 0x00000201 (dwSize)
0x7c347f98, # RETN (ROP NOP) [msvcr71.dll]
0x7c3415a2, # JMP [EAX] [msvcr71.dll]
0xffffffff, #
0x7c376402, # skip 4 bytes [msvcr71.dll]
0x7c351e05, # NEG EAX # RETN [msvcr71.dll]
0x7c345255, # INC EBX # FPATAN # RETN [msvcr71.dll]
0x7c352174, # ADD EBX,EAX # XOR EAX,EAX # INC EAX # RETN [msvcr71.dll]
0x7c344f87, # POP EDX # RETN [msvcr71.dll]
0xffffffc0, # Value to negate, will become 0x00000040
0x7c351eb1, # NEG EDX # RETN [msvcr71.dll]
0x7c34d201, # POP ECX # RETN [msvcr71.dll]
0x7c38b001, # &Writable location [msvcr71.dll]
0x7c347f97, # POP EAX # RETN [msvcr71.dll]
0x7c37a151, # ptr to &VirtualProtect() - 0x0EF [IAT msvcr71.dll]
0x7c378c81, # PUSHAD # ADD AL,0EF # RETN [msvcr71.dll]
0x7c345c30, # ptr to 'push esp #  ret ' [msvcr71.dll]
```

Return-oriented programming

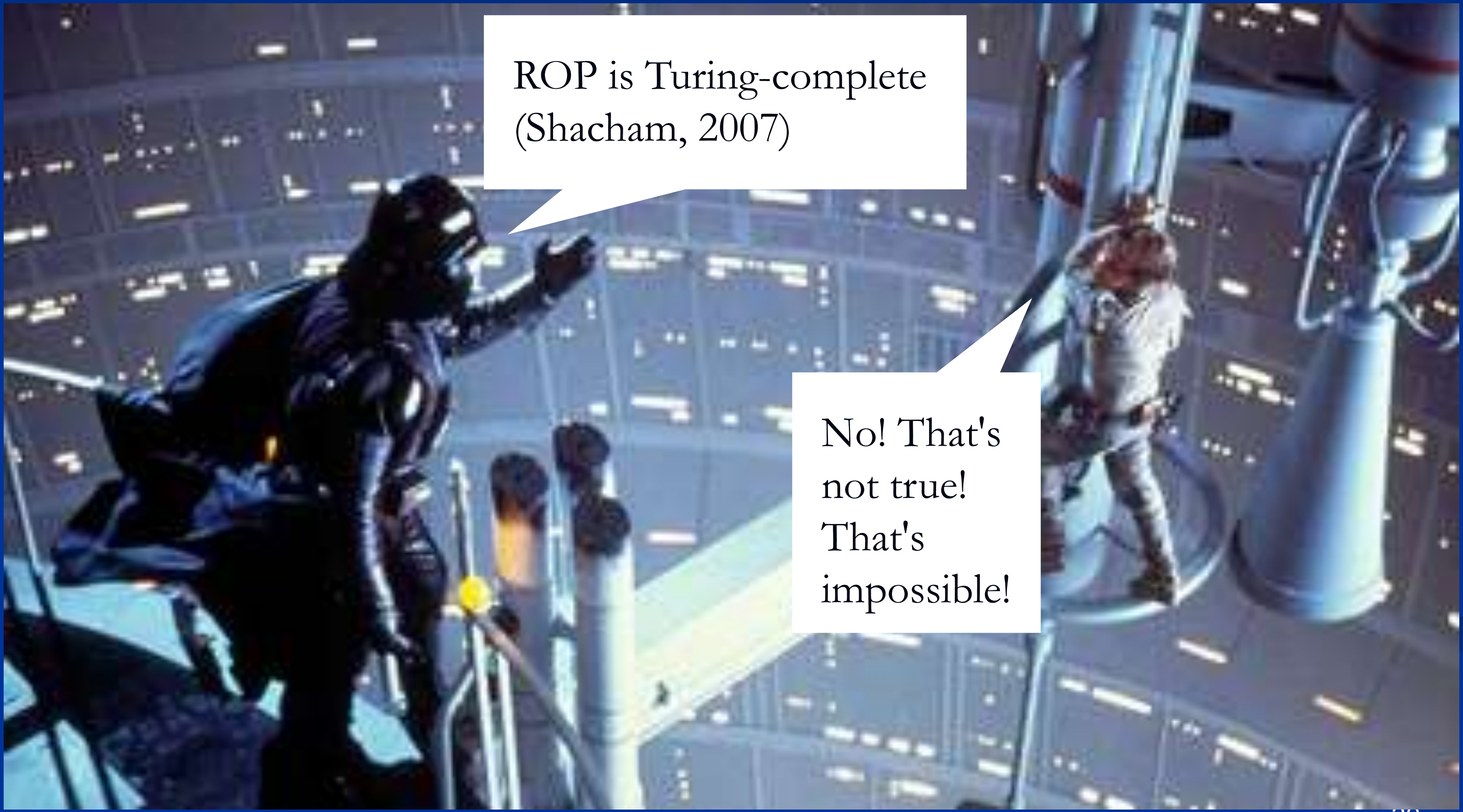
- Unintended instruction sequences
  - Example:

```
7C346C09    0F58C3    ADDPS XMM0,XMM3
```

```
7C346C0A    58        POP EAX
7C346C0B    C3        RETN
```

- Other instructions can be used to connect gadgets instead of RETN:
  - Indirect jumps (jump-oriented programming, JOP)
    - JMP EAX
    - JMP [EAX]
    - JMP [EAX + offset]
  - Indirect calls

The unexpected twist



Mitigations (related work)

- Address Space Layout Randomization (ASLR)
  - Randomizes base address of
    - Executable modules
    - Stack
    - Heap
    - etc.
- Can be bypassed by
  - Using/loading a module that does not support ASLR
  - Using a secondary vulnerability to perform memory disclosure
  - Using the same memory corruption vulnerability to perform both memory disclosure and code execution
    - Example: Memory disclosure technique for Internet Explorer http://ifsec.blogspot.com/2011/06/memory-disclosure-technique-for.html

Mitigations (related work)

- Solutions based on dynammic binray instrumentation
- ROPdefender (Davi et al., 2011)
  - “Shadow stack” approach
  - CALL-RETN relations (ROP: RETN without appropriate CALL)
  - On each CALL, the return address is placed on a shadow stack along with the “real” stack
  - On each RETN, we check if the address on top of the stack is the same as the address on top of the shadow stack
- Drawbacks
  - Dynamic instrumentation introduces overhead of 2x
  - Protects only against RETN-based gadgets

Mitigations (related work)

- Compiler-level approaches
- G-Free (Onarlioglu et al., 2009)
  - Removes all unintended gadgets
  - "Encrypts" return addresses in function prologue and "decrypts" before the function ends
  - Adds stack cookie to all functions with indirect jumps/calls. The cookie is checked before the jump/call is made
- Comprehensive solution, but:
  - Requires knowing the source code
  - Needs to be applied to all modules in order to be effective

Mitigations (related work)

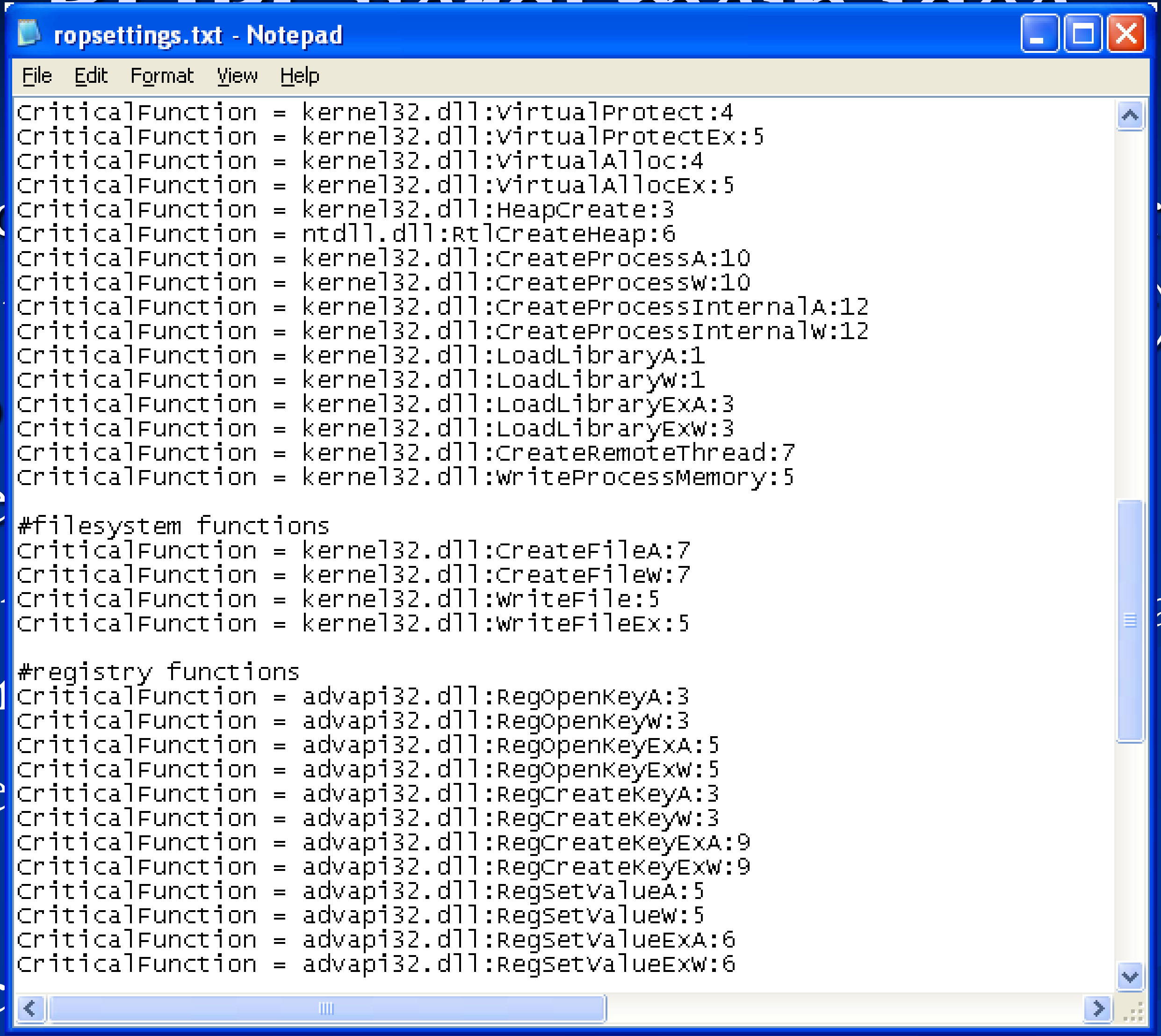
- Static binary rewriting
- In-Place Code Randomization (Pappas et al., 2012)
  - Changes the order of instructions
  - Replaces instructions with ecquivalent ones
- Drawbacks
  - Relies on automated disassembly
    - Not an exact science!
    - Code vs. data
    - Indirect call/jump targets

ROPGuard: main idea

- Requirements:
  - Prototype must be fully functioning and work on Windows
  - Prototype must have low overhead meaning CPU and memory cost of no more than 5%
  - Prototype must not have any application compatibility or usability regressions
- Can we avoid instrumentation/recompiling/rewriting by using the information already present in the process?
- Design practical runtime checks that can be applied at runtime
- When to perform the checks?

ROPGuard: main idea

- In orc ... will need ...) to escap ... proce ...
  - Vir ... ake me ...
  - Cre ...
  - Op ...
  - Etc ...



ropsettings.txt - Notepad

File Edit Format View Help

```
CriticalFunction = kernel32.dll:VirtualProtect:4
CriticalFunction = kernel32.dll:VirtualProtectEx:5
CriticalFunction = kernel32.dll:VirtualAlloc:4
CriticalFunction = kernel32.dll:VirtualAllocEx:5
CriticalFunction = kernel32.dll:HeapCreate:3
CriticalFunction = ntdll.dll:RtlCreateHeap:6
CriticalFunction = kernel32.dll:CreateProcessA:10
CriticalFunction = kernel32.dll:CreateProcessW:10
CriticalFunction = kernel32.dll:CreateProcessInternalA:12
CriticalFunction = kernel32.dll:CreateProcessInternalW:12
CriticalFunction = kernel32.dll:LoadLibraryA:1
CriticalFunction = kernel32.dll:LoadLibraryW:1
CriticalFunction = kernel32.dll:LoadLibraryExA:3
CriticalFunction = kernel32.dll:LoadLibraryExW:3
CriticalFunction = kernel32.dll:CreateRemoteThread:7
CriticalFunction = kernel32.dll:WriteProcessMemory:5

#filesystem functions
CriticalFunction = kernel32.dll:CreateFileA:7
CriticalFunction = kernel32.dll:CreateFileW:7
CriticalFunction = kernel32.dll:WriteFile:5
CriticalFunction = kernel32.dll:WriteFileEx:5

#registry functions
CriticalFunction = advapi32.dll:RegOpenKeyA:3
CriticalFunction = advapi32.dll:RegOpenKeyW:3
CriticalFunction = advapi32.dll:RegOpenKeyExA:5
CriticalFunction = advapi32.dll:RegOpenKeyExW:5
CriticalFunction = advapi32.dll:RegCreateKeyA:3
CriticalFunction = advapi32.dll:RegCreateKeyW:3
CriticalFunction = advapi32.dll:RegCreateKeyExA:9
CriticalFunction = advapi32.dll:RegCreateKeyExW:9
CriticalFunction = advapi32.dll:RegSetValueA:5
CriticalFunction = advapi32.dll:RegSetValueW:5
CriticalFunction = advapi32.dll:RegSetValueExA:6
CriticalFunction = advapi32.dll:RegSetValueExW:6
```

ROPGuard: main idea

- Perform runtime checks when any critical function gets called
- Attempt to answer questions
  - How did the critical function get called?
  - What will happen after the critical function executes?
  - Is the current state of the system consistent with the normal program execution or with the exploitattempt?
  - Will executing the critical function violate the system's security?
- ROPGuard defines 6 runtime checks

ROPGuard: runtime checks(1)

- Check the stack pointer
- Assume: Attacker controls EIP and EAX, but not the stack
  - Stack pivoting

```
MOV ESP, EAX
RETN
```

```
XCHG EAX, ESP
RETN
```

- Thread information block contains information about the area of the memory that was designated for the stack when the thread was created

ROPGuard: runtime checks(2)

- Look for the address of critical function above the top of the stack
- Why?
  - RETN:

    ```
    EIP <- ESP
    ESP <- ESP+4
    ```
  - If we entered critical function via RETN, the address of critical function must be just above the top of the stack
- ROPGuard “saves” a part of the stack upon entering the critical function for examination

ROPGuard: runtime checks(3)

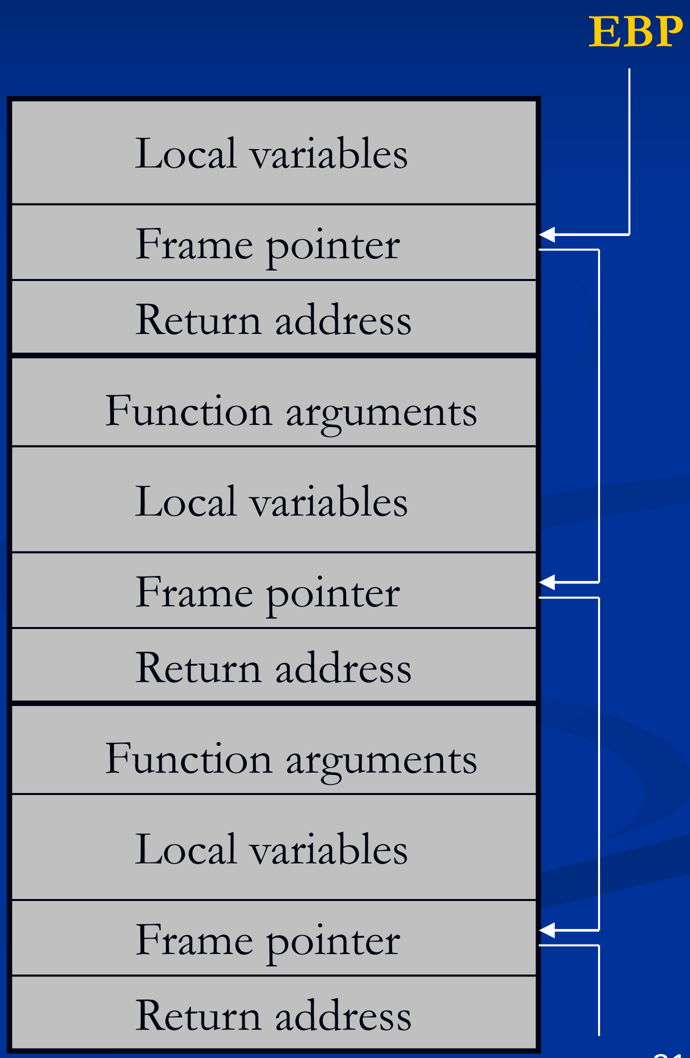
- Return address check
- For each critical function, verify that
  - The return address is executable
  - The instruction at the return address must be preceded with a CALL instruction
  - CALL instruction must lead back to the current critical function

ROPGuard: runtime checks(4)

- Check the call stack
  - Call stack must be valid
- How do we obtain call stack?
- Before RETN

```
mov esp,ebp;
pop ebp;
```

- Return address just below the frame pointer!

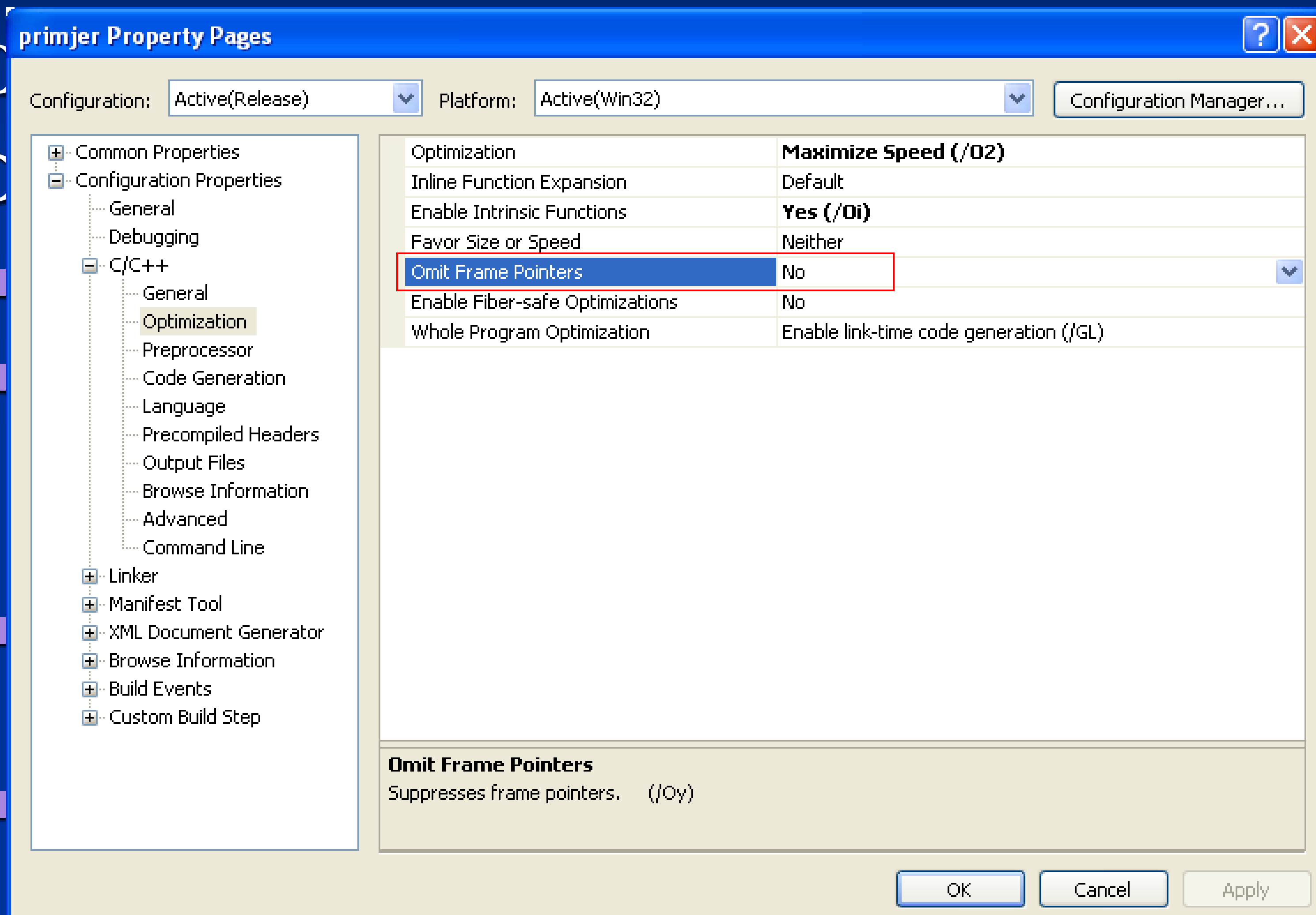


ROPGuard: runtime checks(4)

- Checking the call stack using frame pointers

```
frame_ptr = EBP;
for a specified number of frames
  check if frame_ptr points to the stack;
  return address <- [frame_ptr + 4];
  check if return address is executable;
  check if return address is preceded by call;
  frame_ptr = [frame_ptr];
```

ROPGuard: runtime checks(4)



ROPGuard: runtime checks(5)

- Can we walk the call stack without relying on frame pointers?
- Can we determine the size of the stack frame by relying only on the machine code?

```
                EIP     -> 7C914EEE   MOV AX,WORD PTR DS:[ESI]
      ESP = ESP + 12    -> 7C914EF1   ADD ESP,0C
                           7C914EF4   CMP AX,WORD PTR DS:[ESI+2]
                           7C914EF8   JNB SHORT ntdll.7C914F01
                           7C914EFA   SHR EDI,1
                           7C914EFC   AND WORD PTR DS:[EBX+EDI*2],0
       ESP = ESP + 4    -> 7C914F01   POP EBX
                           7C914F02   XOR EAX,EAX
       ESP = ESP + 4    -> 7C914F04   POP EDI
       ESP = ESP + 4    -> 7C914F05   POP ESI
RETURN ADDRESS = [ESP]  -> 7C914F07   RETN
```

ROPGuard: runtime checks(5)

- ROPGuard simulates control flow from return address of the critical function to the next return instruction and keeps track of ESP along the way
  - Repeat from the return address
- Potential problems
  - Stack frame determined dynamically
    - Very rare in practice
  - stdcall calling convention in combination with
  - Indirect calls: `CALL EAX; CALL [EAX]` etc.

ROPGuard: runtime checks(5)

- ROPGuard brakes simulation when it reaches an instruction for which it cannot resolve ESP
- Possible extension: simulate entire instruction set
- For the time being:

```
0x7c37653d, # POP EAX # POP EDI # POP ESI # POP EBX # POP EBP # RETN
0xfffffdff, # Value to negate, will become 0x00000201 (dwSize)
0x7c347f98, # RETN (ROP NOP) [msvcr71.dll]
0x7c3415a2, # JMP [EAX] [msvcr71.dll]
0xffffffff, #
0x7c376402, # skip 4 bytes [msvcr71.dll]
0x7c351e05, # NEG EAX # RETN [msvcr71.dll]
0x7c345255, # INC EBX # FPATAN # RETN [msvcr71.dll]
0x7c352174, # ADD EBX,EAX # XOR EAX,EAX # INC EAX # RETN [msvcr71.dll]
0x7c344f87, # POP EDX # RETN [msvcr71.dll]
0xffffffc0, # Value to negate, will become 0x00000040
0x7c351eb1, # NEG EDX # RETN [msvcr71.dll]
0x7c34d201, # POP ECX # RETN [msvcr71.dll]
0x7c38b001, # &Writable location [msvcr71.dll]
0x7c347f97, # POP EAX # RETN [msvcr71.dll]
0x7c37a151, # ptr to &VirtualProtect() - 0x0EF [IAT msvcr71.dll]
0x7c378c81, # PUSHAD # ADD AL,0EF # RETN [msvcr71.dll]
0x7c345c30, # ptr to 'push esp #  ret ' [msvcr71.dll]
```

ROPGuard: runtime checks(6)

- Function-specific checks
  - Do not allow program to make stack executable
  - Do not allow program to load .dll-s from the network

ROPGuard: Implementation details

- ROPGuard is implemented as a command line tool and a .dll
- Process is started in a suspended state
- dll injection via CreateRemoteThread()
- When the dll is loaded
  - Hooks all critical function to perform appropriate checks using inline hooking
  - Function header is replaced with a direct jump to

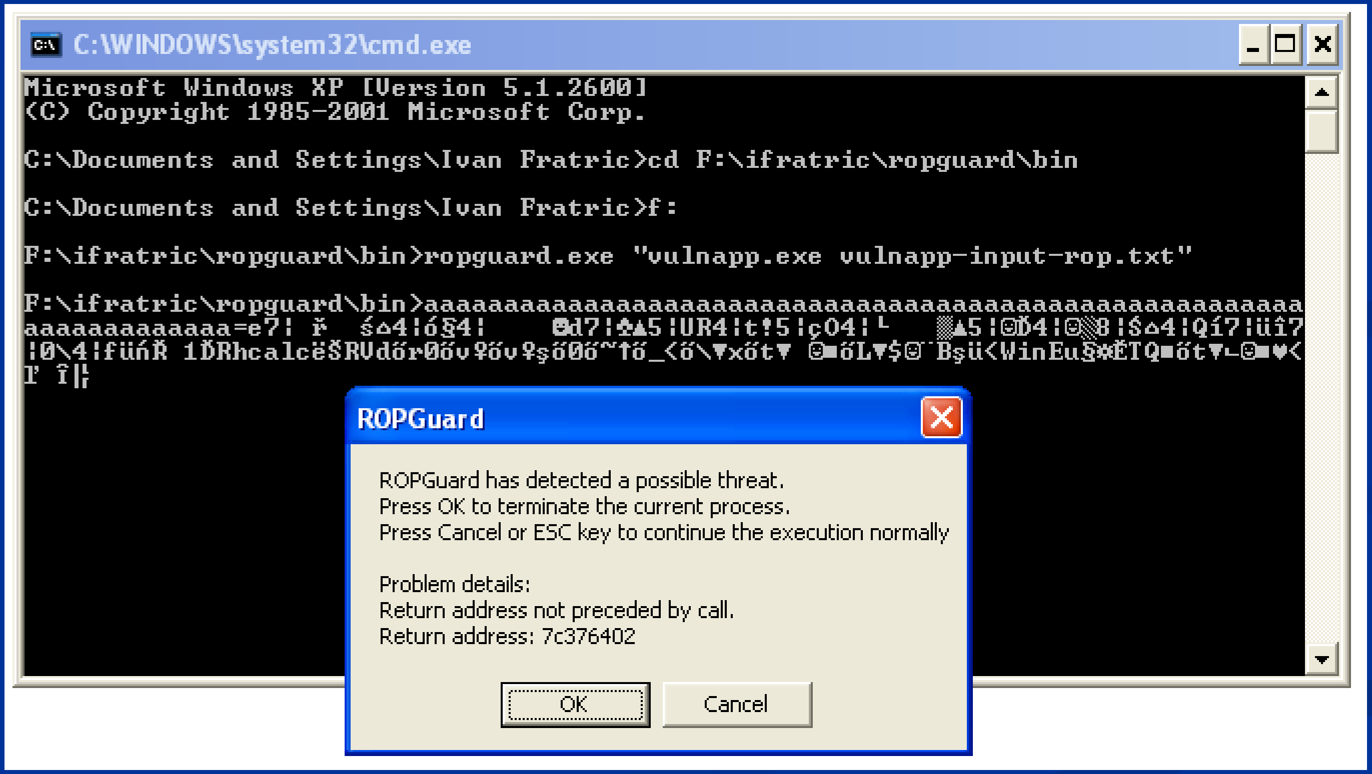
```
SUB ESP, PRESERVE_STACK; //save part of the stack for later examination
PUSHAD; //save the state of all registers at the moment of function call
PUSH ESP; //pointer to the stored registers array
PUSH ORIGINAL_FUNTION_ADDRESS; //address of the current critical function
CALL RopCheck; //perform the appropriate checks
ADD ESP, PRESERVE_STACK+32; //restore the stack pointer
//resume normal function execution
[original function header]
JMP ORIGINAL_FUNTION_ADDRESS + size of original function header;
```

ROPGuard: Implementation details

- Whenever a process creates another (child) process, dll is injected into this process as well
- Cache information about executable module (avoids repeated calls to VirtualQuery)
- ROPGuard can be used to protect processes that are already running
- Extensive configuration options
  - Define what checks to perform
  - Define critical functions

ROPGuard: Evaluation

- Experiments on an example vulnerable application



ROPGuard: Evaluation

- A series of benchmarks was performed to determine the computing overhead

Benchmark name	Benchmark type	Score, not protected	Protected, no cache		Protected, with cache	
			Score	Overhead	Score	Overhead
PCMark Vantage	System	5049*	5009*	0,80 %	5024*	0,50%
NovaBench	System	799*	784*	1,91%	789*	1,27%
Peacekeeper	Browser	1480*	1406*	5,26%	1481*	-0,07%
SunSpider	Browser	247,7 s	253,8 s	2,46%	248,3 s	0,24%
3DMark06	Gaming	7994*	7992*	0,03%	7996*	-0,03%
SuperPI 16M	CPU	403,0 s	399,5 s	-0,87%	406,9 s	0,97%
Average overhead				**1,59%**		**0,48%**

- 0 false positives while running the benchmarks with the default configuration.

ROPGuard: Evaluation

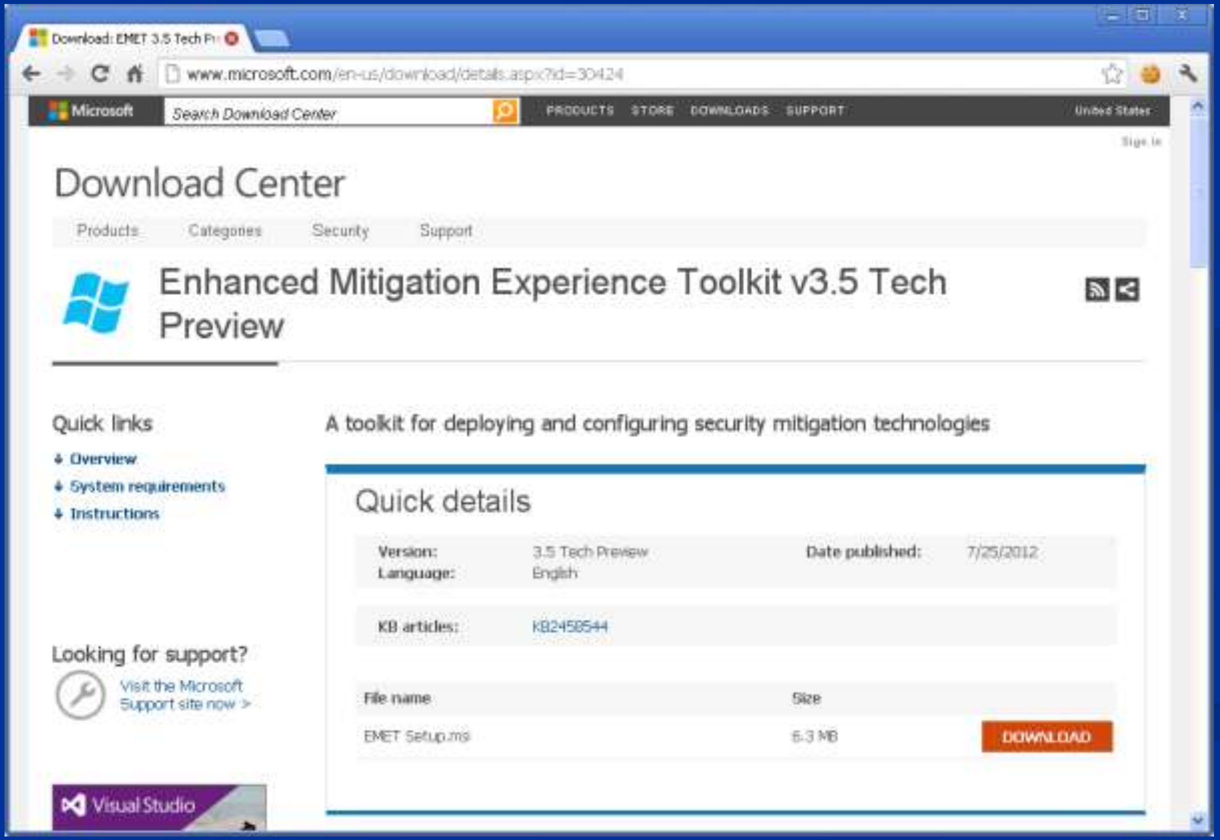
- ROPGuard .dll is just 48kB in size.
- Additional memory overhead introduced by copy-on-write memory page protection

ROPGuard: Evaluation

- ROPGuard won the second prize in Microsoft's BlueHat Prize contest at Black Hat USA 2012

ROPGuard: Evaluation

- ROPGuard has been integrated with Microsoft's EMET tool
  - Enhanced Mitigation Experience Toolkit



Conclusion

- Preventing ROP is a difficult problem
  - Still largely unsolved!
- ROPGuard
  - Can detect currently used ROP attacks
    - Raises the bar for the attacker, more costly exploit development
  - Easy to deploy to protect existing programs
  - Low CPU and memory overhead
- Source code and documentation available at http://code.google.com/p/ropguard/

Ideas for future contests

- Contest evaluation criteria
  - 40.00% - Impact (Strongly mitigate modern threats?)
  - 30.00% - Robustness (Easy to bypass?)
  - 30.00% - Practical and Functional
- Find ways to improve the reliability of binary rewriting
  - Modify binary without breaking basic blocks
    - Removal of unintended gadgets
    - Binary modification relying on unintended instruction sequences
  - Code randomization
    - Resolve code-vs-data and basic blocks dilemma by running the original binary
    - On the first run, the code is modified, later only the modified code is run

Other contest finalists

- KBouncer (V. Pappas, 2012)
  - Recent Intel CPUs support Last Branch Recording (LBR)
  - Stores the last branches in a set of 16 model specific registers (MSRs), can be read using rdmsr instruction
    - Recordv only return instructions
    - On every system call check if call instruction precedes the return address

Other contest finalists

- /ROP (J. DeMott, 2012)
  - Compiler-level solution
  - Makes a list of valid return addresses
  - Requires interrupt on each return instruction
    - Check if the return address is in the whitelist

ROPGuard: runtime checks(5)

```
EIP = return address of critical function;
for a specified number of instructions
   decode instruction at [EIP];
   update EIP;
   if current instruction changes ESP
       update ESP;
   else if current instruction is RETN
       check if return address is executable;
       check if return address is preceded by call;
   else if current instruction changes ESP in an
   unresolvable way
       break sumulation;
```