Improving Software Security with Dynamic Binary Instrumentation

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The Good

- Software vulnerability mitigations are an effective approach at making exploitation more { difficult | expensive | ineffective }

- Mitigations have been developed for most major memory-related vulnerability classes

The Bad

- Due to the difficulty of development, mitigations are almost exclusively developed by vendors (with a few short-lived exceptions)

- Vendors supply mitigation technologies but do not enforce their use by 3rd party developers.

The Ugly

- Understanding and defeating mitigations are a top priority for vulnerability researchers regardless of domain

- Current vendor mitigations are defeated by modern exploitation techniques

The Challenge

- Determine if current binary instrumentation frameworks provide the required technology to develop one-off custom mitigations

- Criteria
  - Stability
  - Speed
  - Ease of implementation

DYNAMIC BINARY INSTRUMENTATION

Dynamic Binary Instrumentation

- Dynamic Binary Instrumentation (DBI) is a process control and analysis technique that involves injecting instrumentation code into a running process

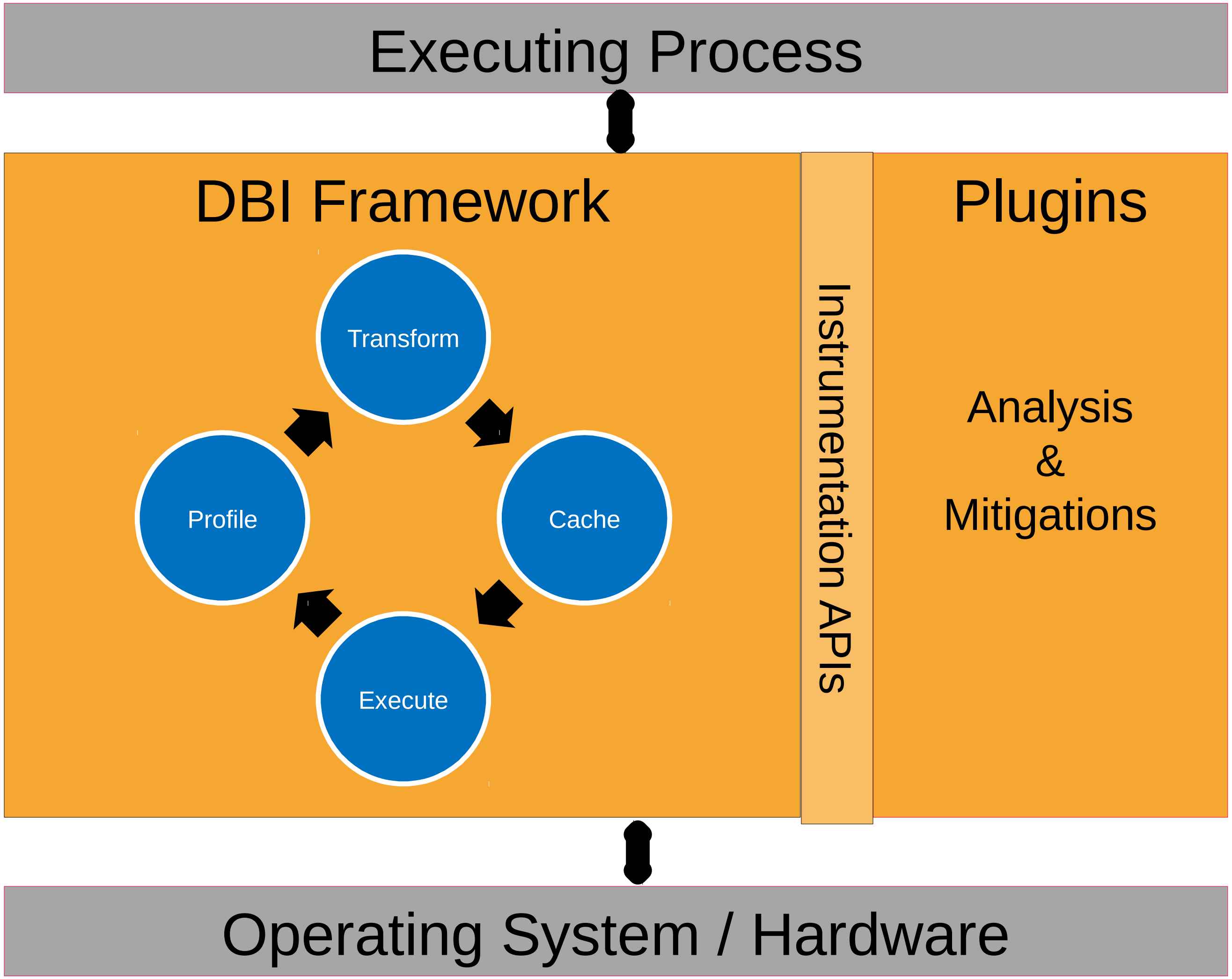
- DBI can be achieved through various means
  - System debugging APIs
  - Binary code caching
  - Virtualization / Emulation

DBI Frameworks

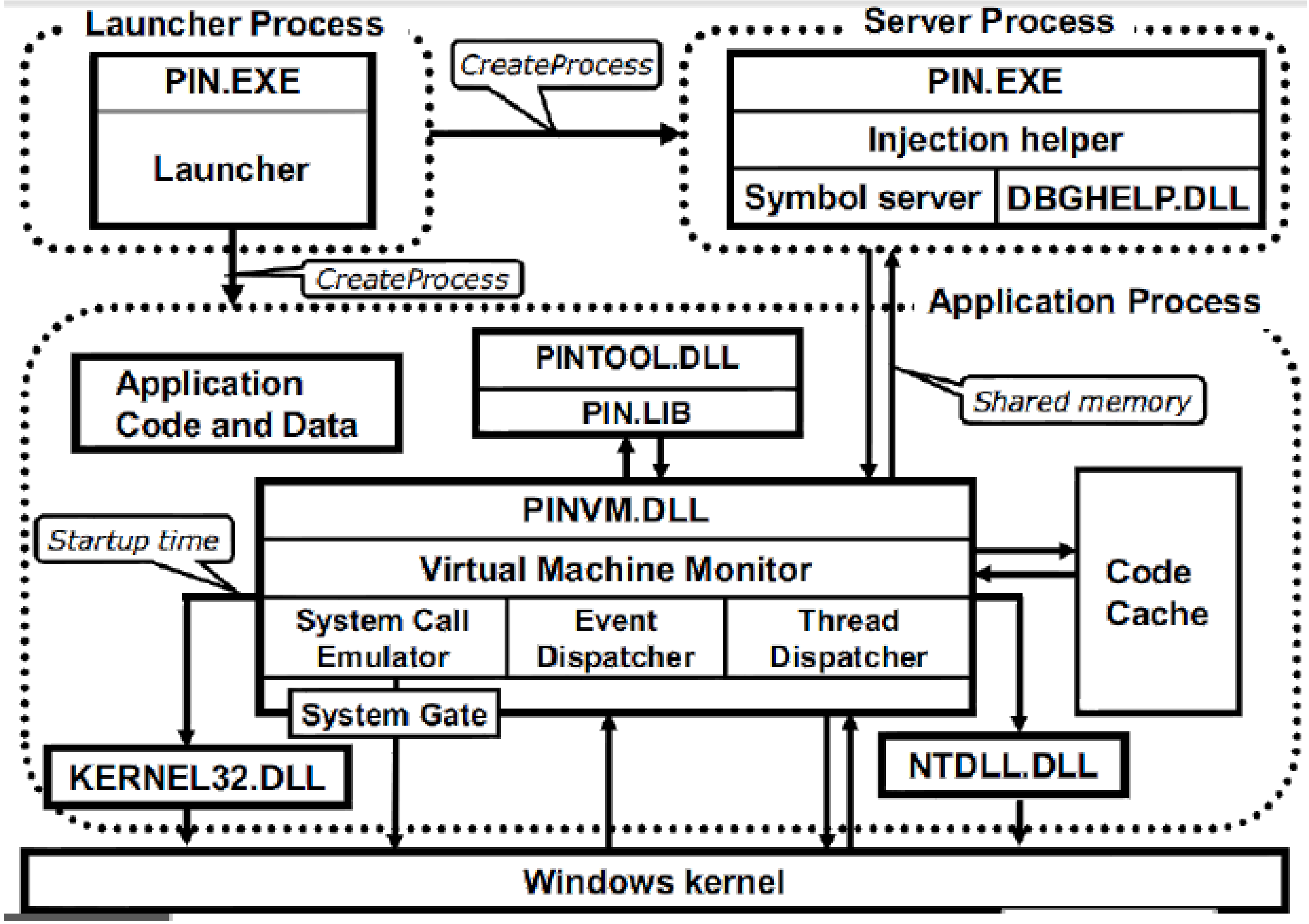
- A DBI Framework facilitates the development of Dynamic Binary Analysis (DBA) tools

- DBI Frameworks provide an API for binary loading, process control, and instrumentation
    - DynamoRIO
    - PIN
    - Valgrind

DBI Architecture



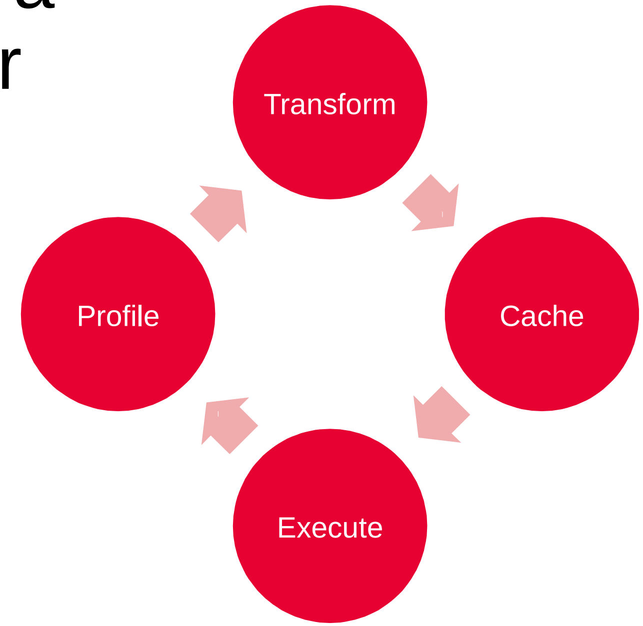
PIN Architecture



Program Loading

- DBI Frameworks parse program binaries and create a code cache or hooks in order for further instrumentation to occur

- Code cache is typically executed rather than original binary mapping



Program Instrumentation

- Frameworks allow the registration of callbacks to handle events and insert instrumentation code
- Callbacks are considered instrumentation routines and injected code are considered analysis routines

Program Instrumentation

- Instrumentation hooks occur at varying granularity
  - Image Load
  - Trace
  - Function / Routine
  - Block
  - Instruction

Process Execution Events

- Callbacks for process execution events can be registered in addition to code loading events
  - Exceptions
  - Process attach
  - Process detach
  - Fini
  - Thread start
  - Thread exit

DBA Plugins

- Existing research has shown several uses for DBI frameworks
  - Diagnostic execution tracing
    - Call graph
    - Code coverage
    - Dataflow tracing
  - Heap profiling and validation
    - Think Application Verifier
  - Cache profiling

DBA Plugins

- Existing research has shown several uses for DBI frameworks
  - Mitigations
    - “Secure Execution Via Program Shepherding”
    - Control Flow Integrity

- Existing mitigations are not available or do not apply to modern Windows operating systems

Useless Benchmarks

- Benchmarking DBI frameworks is difficult
- The best benchmarks should measure CPU and memory efficiency against a shared analysis core
- We do not have this but lets look at some numbers anyway

Useless Benchmarks

```
C:\tools>yafu\yafu64
06/15/11 13:52:20 v1.20.2 @ BLACKHAWK, System/Build Info:
Using GMP-ECM 6.3, Powered by MPIR 2.1.1
detected Intel(R) Core(TM)2 Duo CPU     T9900  @ 3.06GHz
detected L1 = 32768 bytes, L2 = 6291456 bytes, CL = 64 bytes
measured cpu frequency ~= 3035.702040

===============================================================
======= Welcome to YAFU (Yet Another Factoring Utility) =======
=======             bbuhrow@gmail.com                   =======
=======     Type help at any time, or quit to quit      =======
===============================================================
cached 664581 primes. pmax = 10000079
```

Fibonacci Sequence Benchmark			
	100000	250000	500000
Native	1.42	7.379	28.143
DynamoRIO	1.607	7.472	28.891
PIN	2.402	8.377	29.219

Useless Benchmarks

```
C:\tools>ramspeed\ramspeed-win32.exe
RAMspeed (Win32) v1.1.1 by Rhett M. Hollander and Paul V. Bolotoff, 2002-09

USAGE: ramspeed-win32 -b ID [-g size] [-m size] [-l runs]
-b  runs a specified benchmark (by an ID number):
     1 -- INTmark [writing]          4 -- FLOATmark [writing]
     2 -- INTmark [reading]          5 -- FLOATmark [reading]
     3 -- INTmem                     6 – FLOATmem
…
```

Integer Benchmark (MB/sec)						
	Copy	Scale	Add	Triad	AVG	Time
Native	3451.85	3350.21	4022.76	3990.99	3703.95	23.182
DynamoRIO	3493.26	3335.9	3919.36	3839.93	3647.11	23.635
PIN	3382.53	3331.37	3767.52	3752.16	3558.39	24.633

Useful Benchmarks

- Benchmarks for security use are going to be highly subjective

- Criteria
    - Speed – Is the performance hit tolerable
    - Reliability – Does the tool limit false positives and not cause crashes on its own
    - Ease of Implementation – How long does it take to implement a tool under a particular DBI

RETURN ORIENTED PROGRAMMING

Return Oriented Programming

- Return Oriented Programming (ROP) is the modern term for “return-to-libc” method of shellcode execution

- ROP can be used to bypass DEP
  - VirtualProtect()
  - VirtualAlloc()
  - HeapCreate()
  - WriteProcessMemory()

Gadget Shellcode

- Gadgets are a series of assembly instructions ending in a return instruction

```
## Generic Write-4 Gadget ##

rop += "\xD2\x9F\x10\x10“          # 0x10109FD2 :
                 # POP EAX
                 # RET
rop += "\xD0\x64\x03\x10“          # 0x100364D0 :
                 # POP ECX
                 # RET
rop += "\x33\x29\x0E\x10“          # 0x100E2933 :
                 # MOV DWORD PTR DS:[ECX], EAX
                 # RET
```

- Shellcode is executed by creating a fake call stack that will chain a series of instruction blocks together

Gadget Shellcode

- Gadgets are a series of assembly instructions ending in a return instruction
- Shellcode is executed by creating a fake call stack that will chain a series of instruction blocks together

```
## Grab kernel32 pointer from the stack, place it in
EAX ##

rop += "\x5D\x1C\x12\x10" * 6  # 0x10121C5D :
                               # SUB EAX,30
                               # RETN
rop += "\xF6\xBC\x11\x10"      # 0x1011BCF6 :
                               # MOV EAX, DWORD PTR DS:
[EAX]
                               # POP ESI
                               # RETN
rop += rop_align
```

Gadget Shellcode

- Gadgets are a series of assembly instructions ending in a return instruction

- Shellcode is executed by creating a fake call stack that will chain a series of instruction blocks together

```
## EAX = kernel32 base, get pointer to VirtualProtect()
##

rop += ("\x76\xE5\x12\x10" + rop_align) * 4
                               # 0x1012E576 :
                 # ADD EAX,100
                 # POP EBP
                 # RETN
rop += "\x40\xD6\x12\x10“          # 0x1012D640 :
                 # ADD EAX,20
                 # RETN
rop += "\xB1\xB6\x11\x10“          # 0x1011B6B1 :
                 # ADD EAX,0C
                 # RETN
rop += "\xD0\x64\x03\x10“          # 0x100364D0 :
                 # ADD EAX,8
                 # RETN
rop += "\x33\x29\x0E\x10"      # 0x100E2933 :
                 # DEC EAX
                 # RETN
rop += "\x01\x2B\x0D\x10"          # 0x100D2B01 :
                 # MOV ECX,EAX
                             # RETN
rop += "\xC8\x1B\x12\x10"      # 0x10121BC8 :
                 # MOV EAX,EDI
                 # POP ESI
                 # RETN
```

Gadget Shellcode

```
########## VirtualProtect call placeholder ##########
rop += "\x42\x45\x45\x46"                       #&Kernel32.VirtualProtect() placeholder - "BEEF"
rop += "WWWW"                                   #Return address param placeholder
rop += "XXXX"                                   #lpAddress param placeholder
rop += "YYYY"                                   #Size param placeholder
rop += "ZZZZ"                                   #flNewProtect param placeholder
rop += "\x60\xFC\x18\x10"                       #lpflOldProtect param placeholder 0x1018FC60
{PAGE_WRITECOPY}
rop += rop_align    * 2
########## Grab kernel32 pointer from the stack, place it in EAX ##########
rop += "\x5D\x1C\x12\x10" * 6                   #0x10121C5D :  # SUB EAX,30 # RETN
rop += "\xF6\xBC\x11\x10"                       #0x1011BCF6 :  # MOV EAX,DWORD PTR DS:[EAX] # POP ESI #
RETN
rop += rop_align
########## EAX = kernel pointer, now retrieve pointer to VirtualProtect() ##########
rop += ("\x76\xE5\x12\x10" + rop_align) * 4     #0x1012E576 :  # ADD EAX,100 # POP EBP # RETN
rop += "\x40\xD6\x12\x10"                       #0x1012D640 :  # ADD EAX,20 # RETN
rop += "\xB1\xB6\x11\x10"                       #0x1011B6B1 :  # ADD EAX,0C # RETN
rop += "\xD0\x64\x03\x10"                       #0x100364D0 :  # ADD EAX,8 # RETN
rop += "\x33\x29\x0E\x10"                       #0x100E2933 :  # DEC EAX # RETN
rop += "\x01\x2B\x0D\x10"                       #0x100D2B01 :  # MOV ECX,EAX # RETN
rop += "\xC8\x1B\x12\x10"                       #0x10121BC8 :  # MOV EAX,EDI # POP ESI # RETN
```

Small section of shellcode showing several gadgets chained together to locate kernel32!VirtualProtect()

Finding Gadgets

- Useful gadgets typically modify a pointer or cause a load or store operation
  - ADD, SUB, DEC, INC, DEC, PUSH, POP, XCHG, XOR

- Tools now exist for finding gadgets
  - msfpescan
  - Pvefindaddr – PyCommand for ImmunityDbg

Detecting ROP

- ROP requires the use of sub-sections of program blocks to create Gadgets
- Gadgets end in a RET instruction
- Normal program semantics generate call stacks that return to a code location immediately after a CALL or JMP instruction

Detecting ROP

- Algorithm

```
INSTRUMENT_PROGRAM
for each IMAGE
    for each BLOCK in IMAGE
        insert BLOCK in BLOCKLIST
        for each INSTRUCTION in BLOCK
            if INSTRUCTION is RETURN or BRANCH
                insert code to retrieve SAVED_EIP from stack
                insert CALL to ROP_VALIDATE(SAVED_EIP) before INSTRUCTION



ROP_VALIDATE
if SAVED_EIP not in BLOCKLIST
    exit with error warning
```

Detecting ROP

- Implementation
  - The initialization for our pintool is as simple as opening a log file and adding a couple hooks

```
int main(int argc, char *argv[])
{
    PIN_InitSymbols();
    if(PIN_Init(argc,argv))
    {
        return Usage();
    }

    outfile = fopen("c:\\tools\\antirop.txt", "w");
    if(!outfile)
    {
        LOG("Error opening log file\n");
        return 1;
    }

    PIN_AddFiniFunction(Fini, 0);
    TRACE_AddInstrumentFunction(Trace, 0);

    LOG("[+] AntiROP instrumentation hooks 
installed\n");

    PIN_StartProgram();

    return 0;
}
```

Detecting ROP

- Implementation
    - This function implements the callback function when PIN loads a trace of basic blocks the first time and instruments RET instructions

```
VOID Trace(TRACE trace, VOID *v)
{
    ADDRINT addr = TRACE_Address(trace);

    // Visit every basic block in the trace
    for (BBL bbl = TRACE_BblHead(trace);
         BBL_Valid(bbl);
         bbl = BBL_Next(bbl))
    {
        for(INS ins = BBL_InsHead(bbl);
            INS_Valid(ins);
            ins=INS_Next(ins))
        {
            ADDRINT va = INS_Address(ins);
            if(INS_IsBranchOrCall(ins))
            {
                Calls.insert(va);
            }

            if(INS_IsRet(ins))
            {
                INS_InsertCall(ins,
                IPOINT_BEFORE,
AFUNPTR(AntiROPRetCheck),
                IARG_INST_PTR,
                IARG_REG_VALUE, REG_STACK_PTR,
                IARG_END);
            }
        }
    }
}
```

Detecting ROP

- Implementation
  - This function executes before every RET or indirect branch is executed to validate the saved return value points to an instruction after a call

```
VOID AntiROPRetCheck(ADDRINT va, ADDRINT esp)
{
    UINT32 *ptr = (UINT32 *)esp;

    for(int i = 0; i < 4; i++)
    {
        if(*(ptr + i) == 0x90909090)
        {
             fprintf(outfile,
      "NOPS FOUND AT ESP + %d: [%x] = 0x90909090\n",
      i, ptr + i);
        }
    }

    CallsIter = Calls.find(*ptr);
    if (CallsIter != Calls.end())
    {
        count = 0;
    }
    else if(++count > threshold)
    {
        ReportAntiROP(*ptr, count, threshold);
    }

    fflush(outfile);
}
```

Detecting ROP

- Output

```
C:\tools>pin\pin.bat -t mypintool.dll -AntiROPRet -- kmplayer\KMPlayer.exe
C:\tools>type antirop.txt
NOPS FOUND AT ESP + 1: [1196b5f4] = 0x90909090
NOPS FOUND AT ESP + 2: [1196b5f8] = 0x90909090
NOPS FOUND AT ESP + 3: [1196b5fc] = 0x90909090
ANTI-ROP detected an attempted RET to 100ebf17 without using a CALL .. exiting
```

DEMO

Other Mitigations

- ROPDefender
  - Shadow stack
    - Hook before CALL to store return address
    - Hook before RET to determine if returning to address stored before CALL

- SHAN
  - Branch monitoring
    - Store each valid basic block in a list before execution
    - At runtime verify branch destination is in list

JUST-IN-TIME SHELLCODE

Just-In-Time Shellcode

- Just-in-Time (JIT) Shellcode is emitted by a JIT compiler while converting bytecode of an interpreted language to native machine code

- Scripting code such as ActionScript or Javascript is supplied by the user and therefore creates potential for control of native code in the process address space

Just-In-Time Shellcode

- The JIT process creates a writable and executable page with user controlled data
- If an attacker can manipulate the emitted machine code, it can be used to the advantage of the attacker to bypass mitigations

Just-In-Time Shellcode

- Published research has shown that using math operators, specifically XOR, leads to controllable machine code output

```
Operator ADD (+):
[ b8 90 90 90 3c ] mov eax ,03 c909090h
[ f2 0f 2a c0    ] cvtsi2sd xmm0 , eax
[ 66 0f 28 c8    ] movapd xmm1 , xmm0
[ f2 0f 58 c8    ] addsd xmm1 , xmm0
[ f2 0f 58 c8    ] addsd xmm1 , xmm0
```

VS

```
Operator XOR (^):
[ b8 90 90 90 3c ] mov eax , 3c909090h
[ 35 90 90 90 3c ] xor eax , 3c909090h
[ 35 90 90 90 3c ] xor eax , 3c909090h
[ 35 90 90 90 3c ] xor eax , 3c909090h
[ 35 90 90 90 3c ] xor eax , 3c909090h
[ 35 90 90 90 3c ] xor eax , 3c909090h
[ 35 90 90 90 3c ] xor eax , 3c909090h
```

Just-In-Time Shellcode

- Published research has shown that using math operators, specifically XOR, leads to controllable machine code output

```
var y=(0x11223344^0x44332211^0x44332211…);

Compiles as:

0x909090: 35 44 33 22 11  XOR EAX, 11223344
0x909095: 35 44 33 22 11  XOR EAX, 11223344
0x90909A: 35 44 33 22 11  XOR EAX, 11223344
```

Just-In-Time Shellcode

- Published research has shown that using math operators, specifically XOR, leads to controllable machine code output

```
Disassemble at a byte offset to get useful code:

0x909091: 44                     INC ESP
0x909092: 33 22                  XOR ESP, [EDX]
0x909094: 11 35 44 33 22 11      ADC [11223344], ESI
0x90909A: 35 44 33 22 11         XOR EAX, 11223344
```

Just-In-Time Shellcode

- The native behavior of the JIT compiler results in an automatic DEP bypass

- Once a usable payload is constructed using specialized arguments around the XOR operator the executable payload must be found

- Heapspray or memory leak
  - See Dion Blazakis’s paper “Interpreter Exploitation”

Detecting JIT Shellcode

- The ActionScript and JavaScript JIT compilers change memory permissions of compiled machine code to R-E rather than RWE before execution

- We have seen that currently known JIT shellcode relies heavily on the XOR operator

Detecting JIT Shellcode

- We can use a simple heuristic by hooking kernel32!VirtualProtect and checking the disassembly for an unusual number of XORs

- Piotr Bania also pointed out a primitive that can be used to identify operators

```
mov        reg , IMM32
operation reg , IMM32
operation reg , IMM32
operation reg , IMM32
…
```

Detecting JIT Shellcode

- Algorithm

```
INSTRUMENT_PROGRAM
Insert CALL to JIT_VALIDATE at prologue to VirtualProtect

JIT_VALIDATE
Disassemble BUFFER passed to VirtualProtect
for each INSTRUCTION
    if INSTRUCTION is MOV_REG_IMM32 then
        while NEXT_INSTRUCTION uses IMM32
            increase COUNT
            if COUNT > THRESHOLD then
                exit with error warning
```

Detecting JIT Shellcode

- Implementation
  - The initialization for our pintool is as simple as opening a log file and adding a couple hooks

```
int main(int argc, char *argv[])
{
    PIN_InitSymbols();
    if(PIN_Init(argc,argv))
    {
        return Usage();
    }

    outfile = fopen("c:\\tools\\antijit.txt", "w");
    if(!outfile)
    {
        LOG("Error opening log file\n");
        return 1;
    }

    IMG_AddInstrumentFunction(ModuleLoad, NULL);

    LOG("[+] AntiJIT instrumentation hooks 
installed\n");

    PIN_StartProgram();

    return 0;
}
```

Detecting JIT Shellcode

- Implementation
  - This function implements the callback function when PIN loads a module so that VirtualProtect may be hooked

```
void ModuleLoad(IMG img, VOID *v)
{
    RTN rtn;

    rtn = RTN_FindByName(img, "VirtualProtect");
    if (RTN_Valid(rtn))
    {
        RTN_Open(rtn);

        RTN_InsertCall(rtn,
            IPOINT_BEFORE,
AFUNPTR(VirtualProtectHook),
            IARG_FUNCARG_ENTRYPOINT_VALUE, 0,  //
lpAddress
            IARG_FUNCARG_ENTRYPOINT_VALUE, 1,  //
dwSize
            IARG_END);

        RTN_Close(rtn);
    }
}
```

Detecting JIT Shellcode

- Implementation
  - This function executes before calls to VirtualProtect to disassemble the target buffer and determine if a JIT shellcode is probable

```
void VirtualProtectHook(VOID *address, SIZE_T dwSize)
{
    // Disassemble buffer into linked list
...
    while(insn && !MOV_IMM32(insn))
        insn = insn->next;

        while(insn)
        {
            if(OP_IMM32(insn)
                count++;

            if(count > threshold)
                ReportAntiJIT();

            insn = insn->next;
         }
}
```

QUESTIONS

Q & A

- VRT information:
  - Web – http://www.snort.org/vrt
  - Blog – http://vrt-sourcefire.blogspot.com/
  - Twitter – @VRT_sourcefire
  - Videos – http://vimeo.com/vrt
  - Labs – http://labs.snort.org

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References