A Comparison of Buffer Overflow Prevention Implementations and Their Weaknesses

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Agenda

- Compiler-Enforced Protection
  - StackGuard
  - StackShield
  - ProPolice
  - Microsoft /GS Compiler Flag
- Kernel-Enforced Protection
  - PaX
  - StackDefender 1 & 2
  - OverflowGuard
- Attack Vector Test Platform
Compiler-Enforced Protection
Compiler-Enforced Approach

• Advantages
  - No system-wide performance impact
  - Intimate knowledge of binary structure

• Disadvantages
  - Requires modification of each protected binary (including shared libraries) and source code must be available
  - Protections must account for each attack vector since execution environment is not protected
Compiler-Enforced Concepts

• Buffer Overflow Prevention is accomplished by protecting control data stored on the stack.

• Re-ordering Stack Variable Storage

• Stack Canaries
  - Random Canary
  - Random XOR Canary
  - Null Canary
  - Terminator Canary
StackGuard

• Pioneered the use of stack canaries.

• Modifications to the function_prologue and function_epilogue generate and validate canaries.

• Canary originally adjacent to return address.

• Latest version protects both return address and frame pointer.

• Canary location is now architecture specific.
StackShield

• Global Ret Stack
  - Return address is placed in the Global Ret Stack whenever a function is called and copied out whenever the function returns.

• Ret Range Check
  - Copies return address to non-writable memory in function_prologue
  - function_epilogue checks against stored return address to detect an overflow.

• Function pointers are also checked to ensure they point to the .text section.
ProPolice SSP

• Implements a safe stack model which rearranges argument locations, return addresses, previous frame pointers and local variables.

• Provides most complete buffer overflow prevention solution of all evaluated compiler-enforced protection software.
Arrays and local variables are all below the return address.
Vulnerable code segment (provided by ProPolice docs):

```c
void bar( void (*func1)() )
{
    void (*func2)();
    char buf[128];
    .......
    strcpy (buf, getenv("HOME"));
    (*func1)(); (*func2)();
}
```

In our example, an overflow in buf could overwrite the function pointers. However, SSP will change this code to....
Using the ProPolice safe stack, the passed function pointer is put in a register or local variable by the compiler.

```c
void bar( void (*tmpfunc1)() )
{
    char buf[128];
    void (*func2)();
    void (*func1)(); func1 = tmpfunc1;
    ........
    strcpy (buf, getenv ("HOME"));
    (*func1)(); (*func2)();
}
```
Microsoft Compiler Extension

• Initial release of Microsoft’s .NET compiler included buffer overflow protection

• .NET compiler protection is a re-incarnation of Crispin Cowan’s StackGuard

• Differences
  - Cookies vs. Canaries
  - Storing in Writable Memory
How the /GS Switch Works

• The GS switch adds a security cookie

• When the cookie check occurs:
  - Original cookie stored in .data section
  - Compared to the cookie on the stack
  - No match security handler called

• Modifications to Exception Handler
  - Can’t point to stack
  - Registered Handler
• Exception Handler Bypass
  - Exception handler points to heap
  - Exception handler points to registered handler

• If the attacker has an arbitrary DWORD overwrite
  - Overwrite the saved cookie
  - Overwrite the security handler function pointer
Kernel-Enforced Protection
Kernel-Enforced Approach

• Advantages
  - Does not require source code or modifications to binaries
  - Kernel has control over the MMU

• Disadvantages
  - Architecture/platform dependant
  - Noticeable performance impact on architectures that don’t natively support non-executable features
Kernel-Enforced Concepts

• Buffer Overflow Prevention is accomplished by applying access controls to the MMU and randomizing process memory layout.

• The goal of kernel-enforced buffer overflow protection is to prevent and contain the following:
  - Introduction/execution of arbitrary code
  - Execution of existing code out of original program order
  - Execution of existing code in original program order with arbitrary data
Memory Management Unit Access Control Lists

• Non-executable (NOEXEC) protection is the most commonly used access control for memory.

• A non-executable stack resides on a system where the kernel is enforcing proper “memory semantics.”
  - Separation of readable and writable pages
  - All executable memory including the stack, heap and all anonymous mappings must be non-executable.
  - Deny the conversion of executable memory to non-executable memory and vice versa.
Address Space Layout Randomization

• Defeats rudimentary exploit techniques by introducing randomness into the virtual memory layout of a process.

• Binary mapping, dynamic library linking and stack memory regions are all randomized before the process begins executing.
• PaX Project’s kernel patches provide an example of one of the more robust kernel-based protection software currently available.

• PaX offers prevention against unwarranted code execution via memory management access controls and address space randomization.
PaX NOEXEC

• NOEXEC aims to prevent execution of arbitrary code in an existing process’s memory space.

• Three features which ultimately apply access controls on mapped pages of memory:
  - executable semantics are applied to memory pages
  - stack, heap, anonymous memory mappings and any section not marked as executable in an ELF file is non-executable by default.
  - ACLs on mmap() and mprotect() prevent the conversion of the default memory states to an insecure state during execution (MPROTECT).
• Implementation of non-executable memory pages that is derived from the paging logic of IA-32 processors.

• Pages may be marked as “non-present” or “supervisor level access”.

• Page fault handler determines if the page fault occurred on a data access or instruction fetch.
  - Instruction fetch – log and terminate process
  - Data access – unprotected temporarily and continue
• Derived from the IA-32 processor segmentation logic

• Linux runs in protected mode with paging enabled on IA-32 processors, which means that each address translation requires a two step process.
  - LOGICAL <-> LINEAR <-> PHYSICAL

• The 3gb of userland memory space is divided in half:
  - Data Segment: 0x00000000 - 0x5fffffff
  - Code Segment: 0x60000000 – 0xbfffffffff

• Page fault is generated if instruction fetches are initiated in the non-executable pages.
PaX MPROTECT

• Prevents the introduction of new executable code to a given task’s address space.

• Objective of the access controls is to prevent:
  – Creation of executable anonymous mappings
  – Creation of executable/writable file mappings
  – Making executable/read-only file mapping writable except for performing relocations on an ET_DYN ELF
  – Conversion of non-executable mapping to executable
• Every memory mapping has permission attributes which are stored in the vm_flags field of the vma structure within the Linux kernel.

• The four attributes which define the permissions of a particular area of mapped memory are:
  - VM_WRITE
  - VM_EXEC
  - VM_MAYWRITE
  - VM_MAYEXEC
The Linux kernel requires VM_WRITE enabled if the VM_MAYWRITE attribute is true. Also applies to VM_EXEC.

PaX must deny WRITE and EXEC permissions on the same page leaving the safe states to be:

- VM_MAYWRITE
- VM_MAYEXEC
- VM_WRITE | VM_MAYWRITE
- VM_EXEC | VM_MAYEXEC
• Address Space Layout Randomization (ASLR) renders exploits which depend on predetermined memory addresses useless by randomizing the layout of the virtual memory address space.

• PaX implementation of ASLR consists of:
  - RANDUSTACK
  - RANDKSTACK
  - RANDMMAP
  - RANDEXEC
• Responsible for randomizing userspace stack.

• Kernel creates program stack upon each execve() system call.
  - Allocate appropriate number of pages
  - Map pages to process’s virtual address space
    • Userland stack usually is mapped at 0xbfffffff

• Randomization is added both in the address range of kernel memory to allocate and the address at which the stack is mapped.
• Responsible for randomizing a task’s kernel stack

• Each task is assigned two pages of kernel memory to be used during the execution of system calls, interrupts, and exceptions.

• Each system call is protected because the kernel stack pointer will be at the point of initial entry when the kernel returns to userspace
PaX RANDMMAP

• Handles the randomization of all file and anonymous memory mappings.

• Linux usually allocates heap space by beginning at the base of a task's unmapped memory and locating the nearest chunk of unallocated space which is large enough.

• RANDMMAP modifies this functionality in do_mmap() by adding a random delta_mmap value to the base address before searching for free memory.
PaX RANDEEXEC

• Responsible for randomizing the location of ET_EXEC ELF binaries.
  - Image must be mapped at normal address with pages set non-executable
  - Image is copied to random location using RANDMMAP logic.

• Page fault handler will handle accesses to both binary images and allow access when proper conditions are met.
NGSEC StackDefender 1.10

• StackDefender implements a unique protection
  - Protection based on ACLs surrounding API calls

• StackDefender files:
  - kernelNG.fer
  - msvcNG.fer
  - ntdNG.fer
  - Proxydll.dll
  - StackDefender.sys
• Hooks ZwCreateFile, ZwOpenFile to detect:
  - kernel32.dll
  - msvcrtd.dll
  - ntdll.dll

• Redirect files to:
  - *NG.fer
__asm
{
    mov eax, 0x64
    lea edx, [esp+0x04]
    int 0x2e
}

• Gateway between User-mode and Kernel-mode
  – KiSystemService
  – call KeServiceDescriptorTable->ServiceTableBase[function_id]
Hooking System Calls

```asm
__asm
{
    cli       ; stop interrupts
    mov edx, ds:ZwCreateFile  ; save function pointer
    mov ecx, ds:KeServiceDescriptorTable ; save KeSDT pointer
    mov ecx, [ecx]            ; Get base
    mov edx, [edx+1]          ; Get function number
    mov edx, [ecx+edx*4]      ; ServiceTableBase
    mov old_func, edx         ; store old function
    mov edx, [edx+1]
    mov dword ptr [ecx+edx*4], offset function_overwrite
    sti
}
```
NG.fer Files

• Used by StackDefender to add randomness to the systems DLL’s image base.

• Makes a copy of system DLLs
  - Kernel32.dll
  - Ntdll.dll
  - Msvcrtdll
What is the Export Address Table (EAT)?

- Used to export a function for other processes

```c
typedef struct _IMAGE_EXPORT_DIRECTORY {
    DWORD   Characteristics;
    DWORD   TimeDateStamp;
    WORD    MajorVersion;
    WORD    MinorVersion;
    DWORD   Name;
    DWORD   Base;
    DWORD   NumberOfFunctions;
    DWORD   NumberOfNames;
    DWORD   AddressOfFunctions;     // RVA from base of image
    DWORD   AddressOfNames;         // RVA from base of image
    DWORD   AddressOfNameOrdinals;  // RVA from base of image
} IMAGE_EXPORT_DIRECTORY, *PIMAGE_EXPORT_DIRECTORY;
```

- To resolve a function export:
  - Obtain the Virtual address of the EAT
  - Walk AddressOfNames, and AddressOfNameOrdinals
  - Index AddressOfFunctions
• Setup KernelNG.fer
  – Modify characteristics of the .reloc section
    • 42000040 (Readable + Discardable + Initialized Data)
    • E2000060 (Executable + Writable + Readable)
  – Copy function stubs
  – Implement Export Address Table Relocation
    • Overwrites function entry point
StackDefender overwrites the following function’s EAT entries:

<table>
<thead>
<tr>
<th>Function</th>
<th>EAT Entry</th>
</tr>
</thead>
<tbody>
<tr>
<td>WinExec</td>
<td>CopyFileA</td>
</tr>
<tr>
<td>CreateProcessA</td>
<td>CopyFileW</td>
</tr>
<tr>
<td>CreateProcessW</td>
<td>CopyFileExA</td>
</tr>
<tr>
<td>CreateThread</td>
<td>CopyFileExW</td>
</tr>
<tr>
<td>CreateRemoteThread</td>
<td>MoveFileA</td>
</tr>
<tr>
<td>GetProcAddress</td>
<td>MoveFileExW</td>
</tr>
<tr>
<td>LoadModule</td>
<td>MoveFileWithProgressA</td>
</tr>
<tr>
<td>LoadLibraryExA</td>
<td>MoveFileWithProgressW</td>
</tr>
<tr>
<td>LoadLibraryExW</td>
<td>DeleteFileA</td>
</tr>
<tr>
<td>OpenFile</td>
<td>LockFile</td>
</tr>
<tr>
<td>CreateFileA</td>
<td>GetModuleHandleA</td>
</tr>
<tr>
<td>CreateFileW</td>
<td>VirtualProtect</td>
</tr>
<tr>
<td>_lopen</td>
<td>OpenProcess</td>
</tr>
<tr>
<td>_lcreat</td>
<td>GetModuleHandleW</td>
</tr>
</tbody>
</table>
StackDefender Overflow Detection

- .reloc from kernelng.fer loads proxydll.dll

- Proxydll.dll exports StackDefender()
  - arg1 = esp+0x0C
  - arg2 = where the function was called from
  - arg3 = integer
  - arg4 = stack address of a parameter

- Proxydll overflow detection
  - Alert API Routine
    - Checks API for strings e.g. cmd.exe
  - Calls VirtualQuery() on arg1 and arg2
    - MEMORY_BASIC_INFORMATION->AllocationBase
  - IsBadWritePtr() called on arg2
Defeating StackDefender

• Shellcode that puts itself on the heap and marks the heap read-only

• Shellcode that calls ntdll functions e.g. ZwProtectVirtualMemory
  - Bypasses API hooks
StackDefender 2.00

- Heavily influenced by PaX
- Moved away from API ACL

- Initial Analysis shows:
  - Hooks ZwAllocateVirtualMemory and ZwProtectVirtualMemory
  - Hooks int 0x0e and int 0x2e
Vulnerabilities in StackDefender

• StackDefender 1.10
  - Blue Screen of Death when calling ZwCreateFile / ZwOpenFile with an invalid ObjectAttribute parameter.

• StackDefender 2.00
  - Blue Screen of Death when ZwProtectVirtualMemory is given an invalid BaseAddress
• OverflowGuard implements PaX page protection

• OverflowGuard hooks Interrupt Descriptor Table entries 0x0e and 0x01.
  - 0x01 -> Debug Exception
  - 0x0e -> Page Fault

• OverflowGuard Files:
  - OverflowGuard.sys
What is the Interrupt Descriptor Table (IDT)?

• Provides array of function pointers as handlers for userland exceptions or events

• Kernel receives interrupt request and dispatches the correct handler

• Interrupt or Exception occurs
  - int 0x03 - breakpoint
  - int 0x0e - invalid memory access
Overwriting IDT

- Use sidt instruction to obtain IDT base

- Load address of interrupt handler
  - IDT base addr + interrupt id * 8

- The Interrupt Gate which OverflowGuard needs to overwrite looks like:

```
<table>
<thead>
<tr>
<th>31-16</th>
<th>15</th>
<th>14-13</th>
<th>12-8</th>
<th>7-5</th>
<th>4-0</th>
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<tbody>
<tr>
<td>Offset</td>
<td>P</td>
<td>D</td>
<td>PL</td>
<td>0-D-1-1-0</td>
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<tr>
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<tr>
<td>Segment Selector</td>
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<tr>
<td>Offset</td>
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</tbody>
</table>
```
OverflowGuard Buffer Overflow Protection

- OverflowGuard sets memory mappings to read-only

- Writing stack or heap when its in read-only mode
  - Causes page fault
    - Updates Permissions

- Page Fault Handler
  - OverflowGuard converts old EIP to physical address
    - Compares old EIP to fault address
      - Then it was an execution attempt
      - Otherwise it was a data access
        » Find memory address
        » Mark it writable/user/dirty
        » Perform dummy read
        » Reset memory permissions to supervisor
Defeating OverflowGuard

• Return-into-libc previously demonstrated by ins1der

• Does not protect third party software
Attack Vector Test Platform
• Provides objective test results to determine gaps in buffer overflow prevention software

• Simulates exploitation of various attack vectors

• Original work by John Wilander
## Attack Vector Test Platform Results

<table>
<thead>
<tr>
<th>Stack overflow to target</th>
<th>PaX</th>
<th>StackGuard</th>
<th>StackShield</th>
<th>ProPolice SSP</th>
<th>Visual Studio .NET</th>
<th>OverflowGuard</th>
<th>StackDefender 1.10</th>
<th>StackDefender 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter function pointer</td>
<td>+</td>
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<td>-</td>
<td>+</td>
<td>+</td>
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<tr>
<td>Parameter longjmp buffer</td>
<td>+</td>
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<td>-</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Return address</td>
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<td>+</td>
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<tr>
<td>Old base pointer</td>
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<td>Function pointer</td>
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<td>Longjmp buffer</td>
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<tr>
<td>Heap/BSS overflow to target</td>
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<td>Pointer on stack</td>
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</tbody>
</table>
Conclusion

• Test results show that there are varying coverage capabilities in the available protection software

• Windows protection has not advanced yet
  – Few compiler options
  – Successful protection of third party applications

• Combination of kernel and compiler-based protection software is currently the best defense.
Thanks

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Questions?