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.

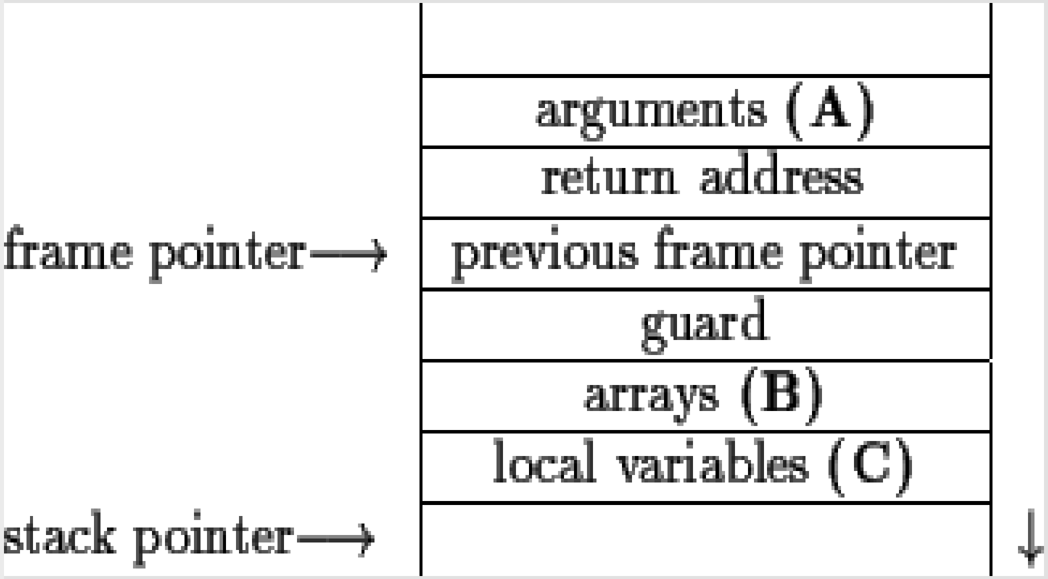
ProPolice SSP

- 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.

ProPolice SSP

- Arrays and local variables are all below the return address.



ProPolice SSP

- Vulnerable code segment (provided by ProPolice docs):

```
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….

ProPolice SSP

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

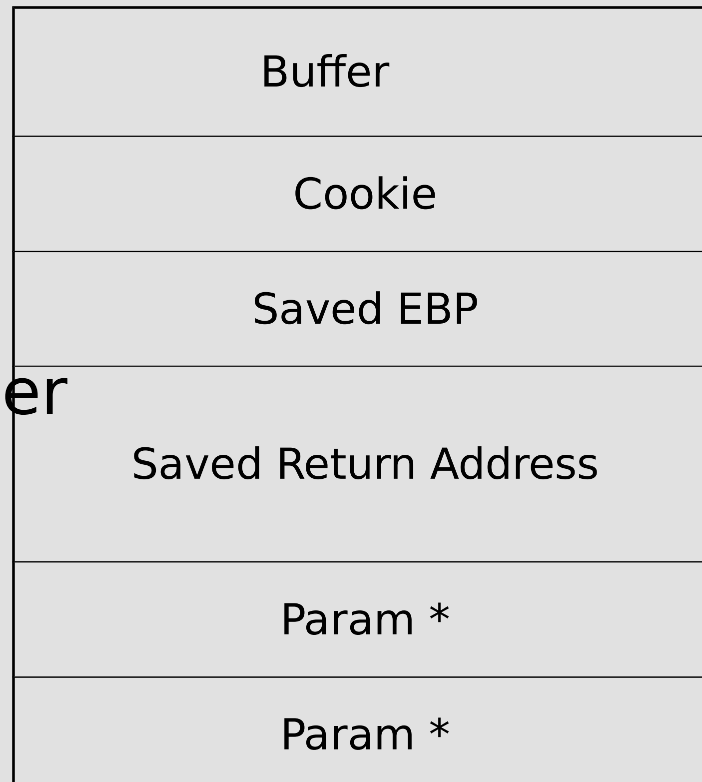
Using the ProPolice safe stack, the passed function pointer is put in a register or local variable by the compiler.

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



.NET Protection Bypass

- 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

- 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).

PaX PAGEEXEC

- 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 – unprotect temporarily and continue

PaX SEGMEXEC

- 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 – 0xbfffffff

- 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

PaX MPROTECT

- 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

PaX MPROTECT

- 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

PaX ASLR

- 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

PaX RANDUSTACK

- 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.

PaX RANDKSTACK

- 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 RANDEXEC

- 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

StackDefender.sys

- Hooks ZwCreateFile, ZwOpenFile to detect:
  - kernel32.dll
  - msvcrt.dll
  - ntdll.dll
- Redirect files to:
  - *NG.fer

Understanding System Calls

```
__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
{
     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
  - Msvcrt.dll

What is the Export Address Table (EAT)?

- Used to export a function for other processes

```
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

kernelNG.fer

- 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

kernelNG.fer (cont.)

StackDefender overwrites the following function’s EAT entries:

- WinExec
- CreateProcessA
- CreateProcessW
- CreateThread
- CreateRemoteThread
- GetProcAddress
- LoadModule
- LoadLibraryExA
- LoadLibraryExW
- OpenFile
- CreateFileA
- CreateFileW
- _lopen
- _lcreat
- CopyFileA
- CopyFileW
- CopyFileExA
- CopyFileExW
- MoveFileA
- MoveFileExW
- MoveFileWithProgressA
- MoveFileWithProgressW
- DeleteFileA
- LockFile
- GetModuleHandleA
- VirtualProtect
- OpenProcess
- GetModuleHandleW

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

DataSecuritySoftware OverflowGuard 1.4

- 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:

31-16	15	14-13	12-8	7-5	4-0
Offset	P	DPL	0-D-1-1-0	0-0-0	Reserved

Segment Selector	15-0
	Offset

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

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

	PaX	StackGuard	StackShield	ProPolice SSP	Visual Studio .NET	OverflowGuard	StackDefender 1.10	StackDefender 2.0
Stack overflow to target								
Parameter function pointer	+	-	-	+	+	-	+	-
Parameter longjmp buffer	+	-	-	-	N/A	N/A	N/A	N/A
Return address	+	+	+	+	+	-	+	-
Old base pointer	+	+	+	+	N/A	N/A	N/A	N/A
Function pointer	+	-	-	+	+	-	+	-
Longjmp buffer	+	-	-	+	N/A	N/A	N/A	N/A
Heap/BSS overflow to target								
Function pointer	+	-	-	-	N/A	N/A	N/A	N/A
Longjmp buffer	+	-	-	-	N/A	N/A	N/A	N/A
Pointer on stack								
Parameter function pointer	+	-	-	+	+	-	+	-
Parameter longjmp buffer	+	-	-	+	N/A	N/A	N/A	N/A
Return address	+	-	+	+	+	-	+	-
Old base pointer	+	+	+	+	N/A	N/A	N/A	N/A
Function pointer	+	-	-	+	+	-	+	-
Longjmp buffer	+	-	-	+	N/A	N/A	N/A	N/A
Pointer on heap/BSS								
Return address	+	-	+	-	N/A	N/A	N/A	N/A
Old base pointer	+	+	+	+	N/A	N/A	N/A	N/A
Function pointer	+	-	-	-	N/A	N/A	N/A	N/A
Longjmp buffer	+	-	-	-	N/A	N/A	N/A	N/A

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.

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Questions?