

Buffer Overflows

- Technique to force execution of malicious code with unauthorized privileges
 - launch a command shell
 - search local disk or network for sensitive data
 - register with command and control network as a zombie
- Can be applied both locally and remotely
- Attack technique is independent of machine architecture and operating system
- Can be tricky to execute, but extremely effective

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Brief History

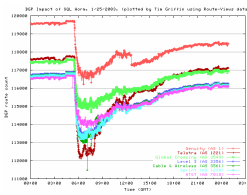
- 1988 Morris worm exploits buffer overflow in fingerd
- 1996 Aleph One publishes classic Phrack article, “Smashing the Stack for Fun and Profit”
- Buffer overflow vulnerabilities found in virtually every application and OS kernel

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Case Study: Slammer



- Worm known as “slammer” or “sapphire” exploited a buffer overflow in MS SQL Server 2000
- Extremely small, the virus transferred itself in a single UDP packet
- Used aggressive, random probing of IPv4 address space
 - may have been initially seeded with a hitlist, an example of a Warhol worm
- Though it caused no direct damage to infected hosts, it succeeded in causing massive network damage

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Definitions

- Buffer:** a contiguous block of computer memory that holds multiple instances of the same type (C arrays)
- Overflow:** to fill over the brim, to fill more than full
- Buffer Overflow:** happens when a program attempts to write data outside of the memory allocated for that data
 - Usually affects buffers of fixed size
- Also known as **Buffer Overrun**

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Process Memory Organization

- Text section (.text)
 - Includes instructions and read-only data
 - Usually marked read-only
 - Modifications cause segment faults
- Data section (.data, .bss)
 - Initialized and uninitialized data
 - Static variables
 - Global variables
- Stack section
 - Used for implementing procedure abstraction

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Simple Example

Off-by-one errors are common and can be exploitable! (see Phrack 55)

```
char B[10];  
B[10] = x;
```

- Array starts at index zero
- So [10] is 11th element
- One byte outside buffer was referenced

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Another Example

```
function foo(char * a) {
    char b[100];
    ...
    strcpy(b, a); // (dest, source)
    ...
}
```

- What is the size of the string located at "a"?
- Is it even a null-terminated string?
- What if it was "strcpy(a, b);" instead?
 - What is the size of the buffer pointed to by "a"?

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What Happens When Memory Outside a Buffer Is Accessed?

- If memory doesn't exist:
 - Bus error
- If memory protection denies access:
 - Segmentation fault
 - General protection fault
- If access is allowed, memory next to the buffer can be accessed
 - Heap
 - Stack
 - Etc...

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Real Example: efingerd.c, v. 1.5

```
• CAN-2002-0423
static char *lookup_addr(struct in_addr
in) {
    static char addr[100];
    struct hostent *he;
    he = gethostbyaddr(...)
    strcpy (addr, he->h_name);
    return addr;
}
```

- How big is he->h_name?
- Who controls the results of gethostbyaddr?
- How secure is DNS? Can you be tricked into looking up a maliciously engineered value?

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Fundamental "C" Problems

- You can't know the length of buffers just from a pointer
 - Partial solution: pass the length as a separate argument
- "C" string functions aren't safe
 - No guarantees that the new string will be null-terminated!
 - Doing all checks completely and properly is tedious and tricky

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"Overflowing" Functions

- gets()
 - void main() {
char buf[512];
gets(buf);
}
- strcpy(), strcat()
 - int main(int argc, char ** argv) {
char buf[512];
strcpy(buf, argv[1]);
}
- sprintf(), vsprintf(), scanf(), sscanf(), fscanf()
- and also your own custom input routines...

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Process Memory Organization

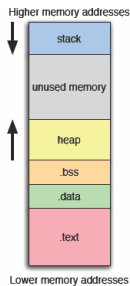
- Heap section
 - Used for dynamically allocated data
- Environment/Argument section
 - Used for environment data
 - Used for the command line data

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Linux x86 Process Layout



- Process memory partitioned into segments
 - `.text` Program code
 - `.data` Initialized static data
 - `.bss` Uninitialized static data
 - `heap` Dynamically-allocated memory
 - `stack` Program call stack
- Each memory segment has a set of permissions associated with it
 - Read, write, and execute (rwx)

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The Stack

- The stack usually grows towards lower memory addresses
- This is the way the stack grows on many architectures including the Intel, Motorola, SPARC, and MIPS processors
- The stack pointer (SP) points to the top of the stack (usually last valid address)

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Frame Structure

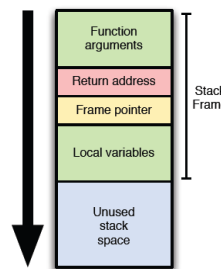
- The stack is composed of frames
- Frames are pushed on the stack as a consequence of function calls (function prolog)
- The address of the current frame is stored in the Frame Pointer (FP) register
 - On Intel architectures EBP is used for this purpose
- Each frame contains
 - The function's actual parameters
 - The return address to jump to at the end of the function
 - The pointer to the previous frame
 - Function's local variables

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Structure of the ix86 Stack



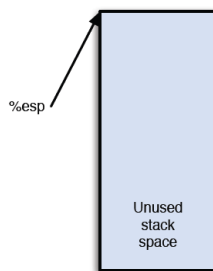
- Used to implement procedure abstraction
- Stack composed of frames, each of which corresponds to a unique function invocation
 - function arguments
 - return address (`eip`)
 - frame pointer (`ebp`)
 - local "automatic" data
- Grows downward from higher to lower memory addresses

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Stack Frame Setup and Teardown



```

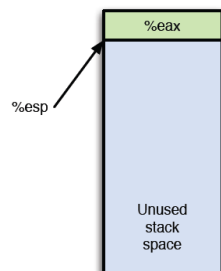
8048716 mov %eax,(%esp)
8048719 call 80485ed<do_chksum>
80485ed push %ebp
80485ee mov %esp,%ebp
80485f1 sub $0x34,%esp
...
804866c add $0x34,%esp
8048670 pop %ebp
8048671 ret
    
```

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Stack Frame Setup and Teardown



```

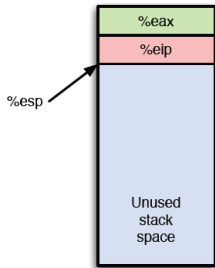
8048716 mov %eax,(%esp)
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Stack Frame Setup and Teardown



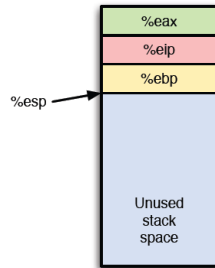
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Stack Frame Setup and Teardown



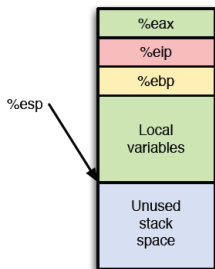
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```

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Stack Frame Setup and Teardown



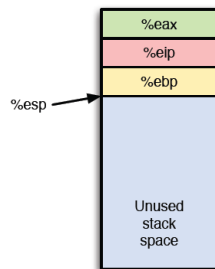
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```

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Stack Frame Setup and Teardown



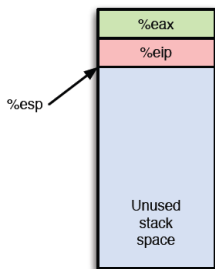
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Stack Frame Setup and Teardown



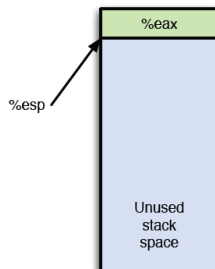
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Stack Frame Setup and Teardown



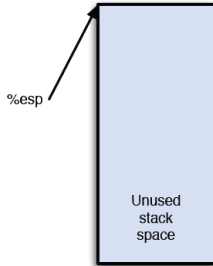
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```

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Stack Frame Setup and Teardown



```

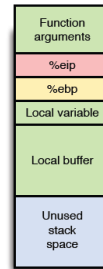
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```

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Vulnerability of Stack Structure



A small problem: return address is inlined with user-controlled buffers

- What can happen if copy into stack-allocated buffer is not bounds-checked?

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Vulnerability of Stack Structure



A small problem: return address is inlined with user-controlled buffers

- What can happen if copy into stack-allocated buffer is not bounds-checked?
- User can control values of other variables, frame pointer, and return address
- If user overwrites the return address on stack, what happens when function returns?

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Vulnerability of Stack Structure



A small problem: return address is inlined with user-controlled buffers

- What can happen if copy into stack-allocated buffer is not bounds-checked?
- User can control values of other variables, frame pointer, and return address
- If user overwrites the return address on stack, what happens when function returns

Result: process will execute arbitrary code of the user's choosing

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Side Effects of Buffer Overflow Depend On

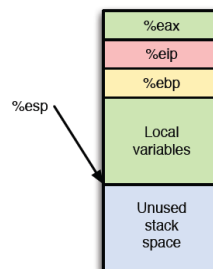
- How much data written past the bounds
- What data is overwritten
- Whether the program attempts to read the data overwritten
- What data replaces the memory that gets overwritten

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Smashing the Stack



```

8048716 mov %eax,(%esp)
8048719 call 80485ed <do_chksum>
80485ed push %ebp
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80485f1 sub $0x34,%esp
...
804866c add $0x34,%esp
8048670 pop %ebp
8048671 ret
    
```

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Smashing the Stack

%eax	...
%ebp	...
	...
Local variables	...
	...
Unused stack space	...

```

8048624 mov 0x8(%ebp),%eax
8048627 mov %eax,0x4(%esp)
804862b lea 0xfffffe4(%ebp),%eax
804862e mov %eax,(%esp)
8048631 call 80483f8 <strcpy@plt>
...
804866c add $0x34,%esp
8048670 pop %ebp
8048671 ret

```

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Smashing the Stack

%eax	...
3133780	...
	...
Local variables	...
	...
Unused stack space	...

```

8048624 mov 0x8(%ebp),%eax
8048627 mov %eax,0x4(%esp)
804862b lea 0xfffffe4(%ebp),%eax
804862e mov %eax,(%esp)
8048631 call 80483f8 <strcpy@plt>
...
804866c add $0x34,%esp
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8048671 ret

```

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Smashing the Stack

%eax	...
3133780	...
	...
Local variables	...
	...
Unused stack space	...

```

8048624 mov 0x8(%ebp),%eax
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```

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Smashing the Stack

%eax	...
3133780	...
	...
Local variables	...
	...
Unused stack space	...

```

8048624 mov 0x8(%ebp),%eax
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...
804866c add $0x34,%esp
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8048671 ret

```

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Smashing the Stack

%eax	...
3133780	...
	...
Local variables	...
	...
Unused stack space	...

```

8048624 mov 0x8(%ebp),%eax
8048627 mov %eax,0x4(%esp)
804862b lea 0xfffffe4(%ebp),%eax
804862e mov %eax,(%esp)
8048631 call 80483f8 <strcpy@plt>
...
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8048670 pop %ebp
8048671 ret

```

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Smashing the Stack

%eax	...
3133780	...
	...
Local variables	...
	...
Unused stack space	...

```

8048624 mov 0x8(%ebp),%eax
8048627 mov %eax,0x4(%esp)
804862b lea 0xfffffe4(%ebp),%eax
804862e mov %eax,(%esp)
8048631 call 80483f8 <strcpy@plt>
...
804866c add $0x34,%esp
8048670 pop %ebp
8048671 ret
3133780 xor %eax,%eax

```

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Memory Layout for Frame



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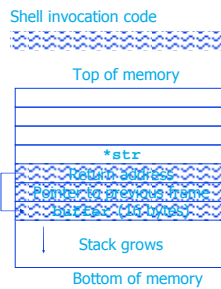
- Data is copied without checking boundaries
- Data “overflows” a pre-allocated buffer and overwrites the return address
- Normally this causes a segmentation fault
- If correctly crafted, it is possible overwrite the return address with a user-defined value
- It is possible to cause a jump to user-defined code (e.g., code that invokes a shell)
- The code may be part of the overflowing data (or not)
- The code will be executed with the privileges of the running program

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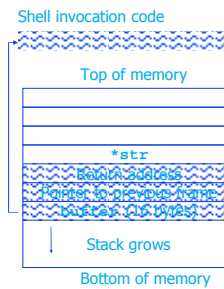


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Buffer Overflow



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How to Exploit a Buffer Overflow

- Different variations to accommodate different architectures
 - Assembly instructions
 - Operating system calls
 - Alignment
- Linux buffer overflows explained in the paper “Smashing The Stack For Fun And Profit” by Aleph One, published on Phrack Magazine, 49(7)
- Most difficult task: generate the correct “payload”

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The Shell Code

```
void main() {  
    char *name[2];  
  
    name[0] = "/bin/sh";  
    name[1] = NULL;  
    execve(name[0], name, NULL);  
    exit(0);  
}
```

- System calls in assembly are invoked by saving parameters either on the stack or in registers and then calling the software interrupt (0x80 in linux)

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High Level View

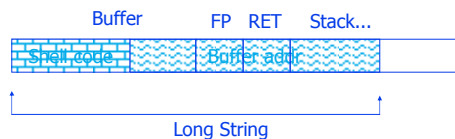
- Compile attack code
- Extract the binary for the piece that actually does the work
- Insert the compiled code into the buffer
 - Before or after the return address
- Figure out where overflow code should jump
- Place that address in the buffer at the proper location so that the normal return address gets overwritten

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Executing the Shell Code



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Guessing the Buffer Address

- In most cases the address of the buffer is not known
 - It has to be “guessed” (and the guess must be very precise)
 - Given the same environment and knowing size of command-line arguments the address of the stack can be roughly guessed
 - The stack address of a program can be obtained by using the function
- ```
unsigned long get_sp(void) {
 __asm__(“movl %esp,%eax”);
}
```
- We also have to guess the offset of the buffer with respect to the stack pointer

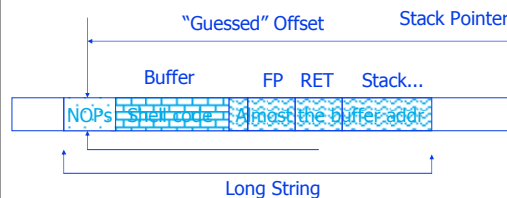
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## NOP Sled

Use a series of NOPs at the beginning of the overflowing buffer so that the jump does not need to be too precise (aka no-operation sled)



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## Heap Overflows

- Overflowing dynamically allocated (heap) buffers may overwrite malloc’s “bookkeeping” structs
- Example struct from dlmalloc

```
struct malloc_chunk {
 INTERNAL_SIZE_T prev_size;
 INTERNAL_SIZE_T size;
 struct malloc_chunk *bk;
 struct malloc_chunk *fd;
};
```

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## Other Buffer Overflows

- Return into libc (control is passed to library call instead of shell code, e.g., system())
- Dtor overflow (C “global” destructor function override)
- C++ VPTR overflows (overwriting C++ virtual function pointers)

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## Remote Buffer Overflows

- Buffer overflow in a network server program can be exercised by an outside user
- Often provides the attacker with an interactive shell on the machine
  - Resulting session has the privileges of the process running the compromised network service
- One of the most common techniques to get remote access to a system

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## Remote Buffer Overflows

- The *egg* is delivered as part of network interaction
- All-time classics
  - NCSA 1.3 httpd
  - INN 1.5
  - Sadmin
  - Bind
  - statd
  - amd
  - IIS
  - Apache HTTP chunked encoding

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## Solutions to Buffer Overflows

- Write decent programs
- Use a language that performs boundary checking (e.g., Java, C#, Python)
- Use Libsafe as a replacement for dangerous functions
- Use fgets, snprintf, strncpy, ...
- Use of canary values on function frames
- Make the stack non-executable (e.g., OpenWall project). This may solve some of the problems but not all of them
- Misuse-based intrusion detection

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## Canaries on a Stack

- Add a few bytes containing special values between variables on the stack and the return address.
- Before the function returns, check that the values are intact.
  - If not, there has been a buffer overflow
    - Terminate program
- If the goal was a Denial-of-Service then it still happens, but the machine is not compromised
- If the canary can be read by an attacker, then a buffer overflow exploit can be made to rewrite the canary

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## Canaries



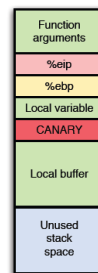
- Technique to detect and prevent buffer overflows by prepending a “canary” to sensitive information
- If canary is “destroyed,” a preceding buffer is assumed to have been overflowed
- Implementations exist for both the stack and heap
  - StackGuard [Cowan97]
  - SSP (aka ProPolice) [Ettoh01]
  - dmalloc heap protection
  - Microsoft Visual C++ /GS

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## Canaries



- Technique to detect and prevent buffer overflows by prepending a “canary” to sensitive information
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## Canaries

Function arguments

0x55531337

Unused stack space

- Technique to detect and prevent buffer overflows by prepending a “canary” to sensitive information
- If canary is “destroyed,” a preceding buffer is assumed to have been overflowed
- Implementations exist for both the stack and heap
  - StackGuard [Cowan97]
  - MemGuard
  - SSP (aka ProPolice) [Etoh01]
  - dlmalloc heap protection
  - Microsoft Visual C++ /GS

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## StackGuard

- Compiler extension to gcc
  - prologue pushes random canary on the stack
  - epilogue checks that canary value unchanged
- Assumes return address is unaltered IFF canary word is unaltered
- Can be bypassed if
  - Overflow skips over the canary word
  - Canary word can be guessed
- Only protects against stack smashing attacks

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## MemGuard

- Protects return address when function is called and unprotects when function returns
- Mark virtual memory pages containing return pointer as read-only and emulates writes to nonprotected words on page
  - 1800 times the cost of normal write
- Use Pentium debug registers to hold return addresses and configure as read only
  - Can only protect top four frames at any time
- Only protects against stack smashing attacks

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## Address Space Layout Randomization (ASLR)

Higher memory addresses

Lower memory addresses

- Technique to randomly perturb locations of memory areas
- Force attacker to guess addresses of important code or data with low probability
- Effectiveness dependent on amount of entropy introduced by scheme
  - increase space within which a memory area may be positioned
  - decreasing the period of perturbation
  - rearranging contents of a memory area
- Various implementations
  - PaX
  - OpenBSD
  - ExecShield

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## Non-executable memory

Higher memory addresses

Lower memory addresses

- Technique to exclusively allocate memory for either code or data
- May be implemented in hardware as PTE write bit or emulated in software
  - SPARC, Alpha, PowerPC, IA-64 processors
  - PaX
  - ExecShield (RedHat)
  - WX (OpenBSD)
  - NX (AMD processors)
  - XD (Intel processors, identical to NX)
  - data execution prevention, or DEP (recent Windows releases)
- Prevents attacker from injecting data to be executed as code

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## Misuse-based Intrusion Detection

### Shellcode

```
90 nop
90 nop
90 nop
90 nop
6a 0b push $0xb
58 pop %eax
99 cld
```

### Signature

content: "[90 90 6a 0b ...]"

- Systems that examine events from the network, host, or application for evidence of malicious behavior
- Attacks described by signatures
  - signature can be modeled as a conjunction of constraints on a time-ordered series of events
  - if all constraints for a signature are satisfied, system assumes an attack has occurred, otherwise events are considered normal
- NIDSs contain many signatures for buffer overflow exploits

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content: "[90 90 6a 0b ...]"

- Unfortunately, there are many ways to write shellcode
  - apply semantics-preserving transformations
  - use decoder routine to obfuscate payload
  - use bootstrap routine to fetch different modules
- Matching against specific exploit payloads is fundamentally the wrong approach
- Rather, should attempt to model conditions leading to exploitation of the vulnerability

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## Misuse-based Intrusion Detection

### Shellcode

```
90 nop
90 nop
58 pop %eax
58 pop %eax
6a 0b push $0xb
58 pop %eax
31 d2 xor %edx,%edx
```

### Signature

content: "[90 90 6a 0b ...]"

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## Misuse-based Intrusion Detection

### Shellcode

```
90 nop
90 nop
58 pop %eax
58 pop %eax
31 c0 xor %eax,%eax
83 c0 0b add $0xb,%eax
31 d2 xor %edx,%edx
```

### Signature

content: "[90 90 6a 0b ...]"

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## Misuse-based Intrusion Detection

### Shellcode

```
90 nop
90 nop
58 pop %eax
58 pop %eax
31 d2 xor %edx,%edx
89 d0 mov %edx,%eax
83 c0 0b add %0xb,%eax
```

### Signature

content:"90 90 6a 0b ...]"

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## Moral of the Buffer Overflow Problem

- Always do bounds checking
- Price of bounds checking is efficiency
  - Generally C favors efficiency in most tradeoffs

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