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

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

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

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"?

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...

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?

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

"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…

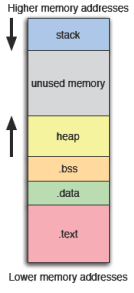
Process Memory Organization

- 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

Process Memory Organization

- Stack section
  – Used for implementing procedure abstraction
- Heap section
  – Used for dynamically allocated data
- Environment/Argument section
  – Used for environment data
  – Used for the command line data

Linux x86 Process Layout



- Process memory partitioned into segments
  .text Program code
  .data Initialized static data
  .bss Unitialized 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)

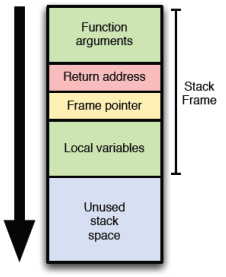
The Stack

- 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)

Frame Structure

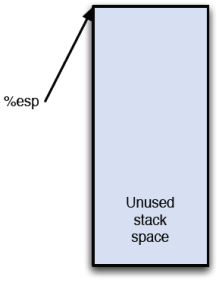
- The stack is composed of frames
- Frames are pushed on the stack as a consequence of function calls (function prolog)
- The address of the current frame is stored in the Frame Pointer (FP) register
  - On Intel architectures EBP is used for this purpose
- Each frame contains
  - The function's actual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

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

Stack Frame Setup and Teardown

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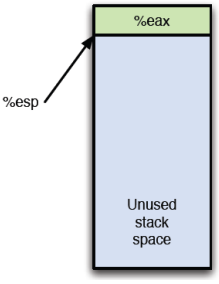


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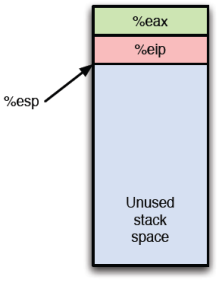


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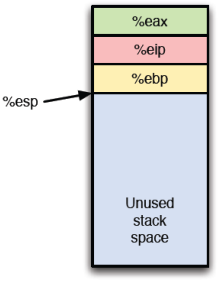


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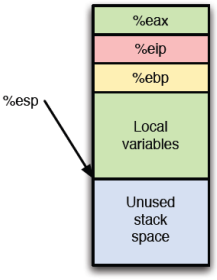


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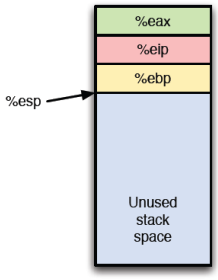


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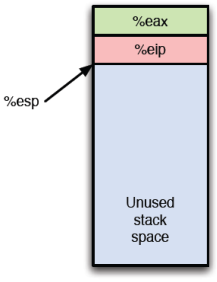


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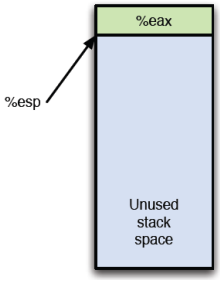


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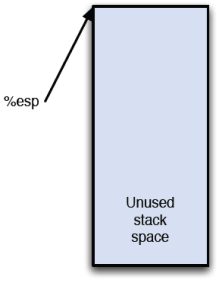


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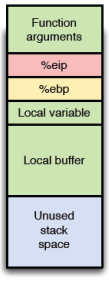

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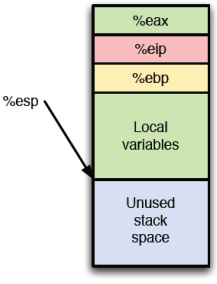
Result: process will execute arbitrary code of the user's choosing

Side Effects of Buffer Overflow Depend On

- How much data is 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

Smashing the Stack

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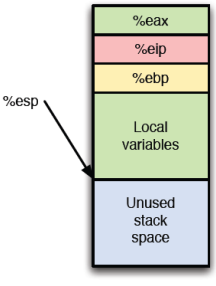


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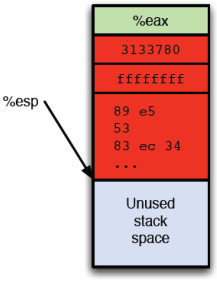


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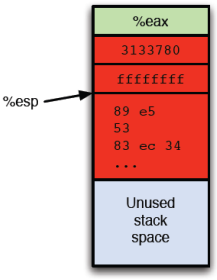


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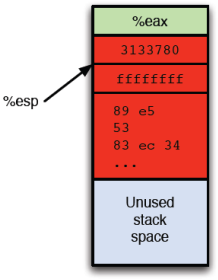


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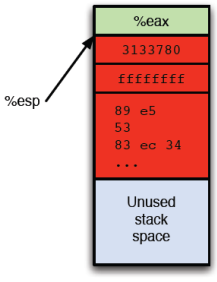


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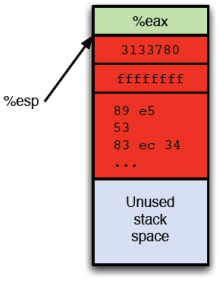


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3133780  xor   %eax,%eax
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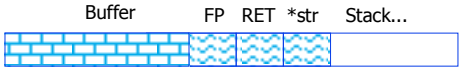
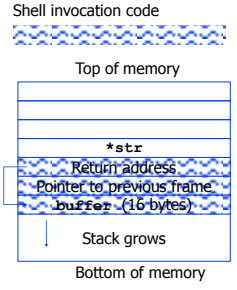
Memory Layout for Frame



Buffer Overflow

- 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

Buffer Overflow



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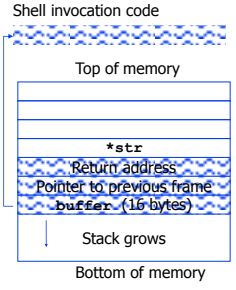


How to Exploit a Buffer Overflow

- 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"

The Shell Code

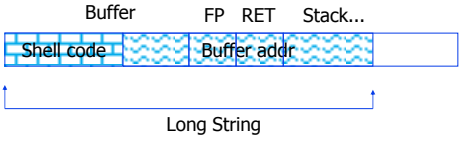
```
void main() {
      char *name[2];

      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)

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

Executing the Shell Code



Guessing the Buffer Address

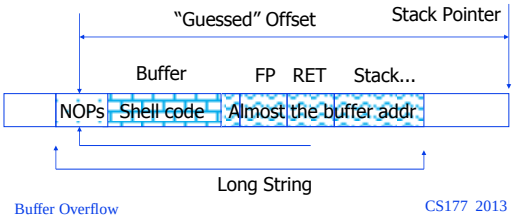
- In most cases the address of the buffer is not known
- It has to be "guessed" (and the guess must be very precise)
- Given the same environment and knowing the size of command-line arguments the address of the stack can be roughly guessed
- The stack address of a program can be obtained by using the 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

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)



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;
};
```


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)

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

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, strncat, 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

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.

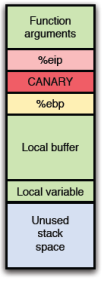
–If not, there has been a buffer overflow

• Terminate program

• If hacker's 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

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) [Etoh01]
  - dlmalloc heap protection
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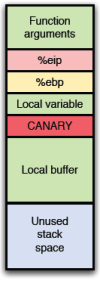

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Canaries

- 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]
  - MemGuard
  - SSP (aka ProPolice) [Etoh01]
  - dlmalloc heap protection
  - Microsoft Visual C++ /GS

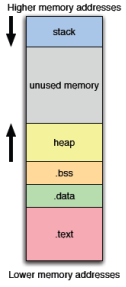
StackGuard

- 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

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

Address Space Layout Randomization (ASLR)



- 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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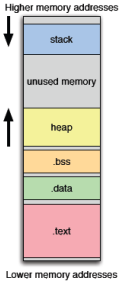

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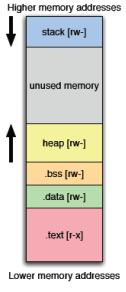
Non-executable memory



- 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

Misuse-based Intrusion Detection

Shellcode

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

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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- 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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83 c0 0b  add     $0xb,%eax
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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