Machine-Level Programming V: Advanced Topics

15-213: Introduction to Computer Systems
9th Lecture, September 27, 2016

Instructor:
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Today

- Memory Layout
- Buffer Overflow
  - Vulnerability
  - Protection
- Unions
x86-64 Linux Memory Layout

- **Stack**
  - Runtime stack (8MB limit)
  - E.g., local variables

- **Heap**
  - Dynamically allocated as needed
  - When call `malloc()`, `calloc()`, `new()`

- **Data**
  - Statically allocated data
  - E.g., global vars, `static` vars, string constants

- **Text / Shared Libraries**
  - Executable machine instructions
  - Read-only

Hex Address  

```
00000000
```

```
40000000
```

```
00007FFFFFFF
```

[Diagram of memory layout with sections labeled Stack, Heap, Data, Text, and Shared Libraries, showing hexadecimal addresses for each section.]
Memory Allocation Example

```c
char big_array[1L<<24]; /* 16 MB */
char huge_array[1L<<31]; /* 2 GB */

int global = 0;

int useless() { return 0; }

int main ()
{
    void *p1, *p2, *p3, *p4;
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    p2 = malloc(1L << 8); /* 256 B */
    p3 = malloc(1L << 32); /* 4 GB */
    p4 = malloc(1L << 8); /* 256 B */
    /* Some print statements ... */
}
```

Where does everything go?

## x86-64 Example Addresses

The addresses shown in the diagram are for the following variables and functions:

- **local**: `0x00007ffe4d3be87c`
- **p1**: `0x00007f7262a1e010`
- **p3**: `0x00007f7162a1d010`
- **p4**: `0x000000008359d120`
- **p2**: `0x000000008359d010`
- **big_array**: `0x0000000080601060`
- **huge_array**: `0x0000000000601060`
- **main()**: `0x000000000040060c`
- **useless()**: `0x0000000000400590`

### Address Range

The address range for these variables and functions is approximately $2^{47}$.
Today

- Memory Layout
- Buffer Overflow
  - Vulnerability
  - Protection
- Unions
Recall: Memory Referencing Bug Example

typedef struct {
    int a[2];
    double d;
} struct_t;

double fun(int i) {
    volatile struct_t s;
    s.d = 3.14;
    s.a[i] = 1073741824; /* Possibly out of bounds */
    return s.d;
}

fun(0)  ->  3.14
fun(1)  ->  3.14
fun(2)  ->  3.1399998664856
fun(3)  ->  2.00000061035156
fun(4)  ->  3.14
fun(6)  ->  Segmentation fault

- Result is system specific
Memory Referencing Bug Example

typedef struct {
    int a[2];
    double d;
} struct_t;

fun(0) -> 3.14
fun(1) -> 3.14
fun(2) -> 3.1399998664856
fun(3) -> 2.00000061035156
fun(4) -> 3.14
fun(6) -> Segmentation fault

Explanation:

critical State | 6 |
| 5 |
| 4 |
| 3 |
| 2 |
| 1 |
| 0 |

struct_t

Location accessed by fun(i)
Such problems are a BIG deal

- Generally called a “buffer overflow”
  - when exceeding the memory size allocated for an array
- Why a big deal?
  - It’s the #1 technical cause of security vulnerabilities
    - #1 overall cause is social engineering / user ignorance
- Most common form
  - Unchecked lengths on string inputs
  - Particularly for bounded character arrays on the stack
    - sometimes referred to as stack smashing
String Library Code

- Implementation of Unix function `gets()`

```c
/* Get string from stdin */
char *gets(char *dest)
{
    int c = getchar();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

- No way to specify limit on number of characters to read

- Similar problems with other library functions
  - `strcpy, strcat`: Copy strings of arbitrary length
  - `scanf, fscanf, sscanf`, when given `%s` conversion specification
Vulnerable Buffer Code

```c
/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}

void call_echo()
{
    echo();
}
```

```
unix> ./bufdemo-nsp
Type a string: 012345678901234567890123
012345678901234567890123
```

```
unix> ./bufdemo-nsp
Type a string: 0123456789012345678901234
Segmentation Fault
```

btw, how big is big enough?
Buffer Overflow Disassembly

echo:

```
00000000004006cf <echo>:
    4006cf: 48 83 ec 18           sub    $0x18,%rsp
    4006d3: 48 89 e7              mov    %rsp,%rdi
    4006d6: e8 a5 ff ff ff       callq  400680 <gets>
    4006db: 48 89 e7              mov    %rsp,%rdi
    4006de: e8 3d fe ff ff       callq  400520 <puts@plt>
    4006e3: 48 83 c4 18           add    $0x18,%rsp
    4006e7: c3                    retq
```

call_echo:

```
4006e8:  48 83 ec 08           sub    $0x8,%rsp
4006ec:  b8 00 00 00 00       mov    $0x0,%eax
4006f1:  e8 d9 ff ff ff       callq  4006cf <echo>
4006f6:  48 83 c4 08           add    $0x8,%rsp
4006fa:  c3                    retq
```
Buffer Overflow Stack

Before call to gets

Stack Frame for call_echo

Return Address (8 bytes)

20 bytes unused

buf ← %rsp

/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}

echo:
    subq $24, %rsp
    movq %rsp, %rdi
    call gets
    ...
Buffer Overflow Stack Example

Before call to gets

Stack Frame for call_echo

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</table>

20 bytes unused

[3] [2] [1] [0]

void echo()
{
    char buf[4];
    gets(buf);
    . . .
}

echo:
    subq $24, %rsp
    movq %rsp, %rdi
    call gets
    . . .

call_echo:
    . . .
    4006f1: callq 4006cf <echo>
    4006f6: add $0x8,%rsp
    . . .

buf ← %rsp
Buffer Overflow Stack Example #1

After call to gets

Stack Frame for call_echo

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```c
void echo()
{
    char buf[4];
    gets(buf);
    ...
}
```

echo:
    subq $24, %rsp
    movq %rsp, %rdi
    call gets
    ...

call_echo:
    ...
    4006f1: callq 4006cf <echo>
    4006f6: add $0x8,%rsp
    ...

buf ← %rsp

unix> ./bufdemo-nsp
Type a string: 01234567890123456789012
01234567890123456789012

“01234567890123456789012\0”

Overflowed buffer, but did not corrupt state
Buffer Overflow Stack Example #2

After call to gets

Stack Frame for call_echo

| 00 | 00 | 00 | 00 |
| 00 | 40 | 00 | 34 |
| 33 | 32 | 31 | 30 |
| 39 | 38 | 37 | 36 |
| 35 | 34 | 33 | 32 |
| 31 | 30 | 39 | 38 |
| 37 | 36 | 35 | 34 |
| 33 | 32 | 31 | 30 |

void echo()
{
    char buf[4];
    gets(buf);
    ...
}

echo:
    subq $24, %rsp
    movq %rsp, %rdi
    call gets
    ...

call_echo:
    ...
    4006f1: callq 4006cf <echo>
    4006f6: add $0x8, %rsp
    ...

buf ← %rsp

unix> ./bufdemo-nsp
Type a string: 0123456789012345678901234
Segmentation Fault

"0123456789012345678901234\0"

Overflowed buffer and corrupted return pointer
Buffer Overflow Stack Example #3

After call to gets

Stack Frame for call_echo

| 00 | 00 | 00 | 00 |
| 00 | 40 | 06 | 00 |
| 33 | 32 | 31 | 30 |
| 39 | 38 | 37 | 36 |
| 35 | 34 | 33 | 32 |
| 31 | 30 | 39 | 38 |
| 37 | 36 | 35 | 34 |
| 33 | 32 | 31 | 30 |

void echo()
{
    char buf[4];
    gets(buf);
    ...
}

echo:
    subq $24, %rsp
    movq %rsp, %rdi
    call gets
    ...

call_echo:
    ...
    4006f1: callq 4006cf <echo>
    4006f6: add $0x8,%rsp
    ...

buf ← %rsp

unix> ./bufdemo-nsp
Type a string: 012345678901234567890123
012345678901234567890123

"012345678901234567890123\0"

Overflowed buffer, corrupted return pointer, but program seems to work!
Buffer Overflow Stack Example #3 Explained

After call to gets

Stack Frame for call_echo

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buf ← %rsp

register_tm_clones:

```
...  
400600:  mov  %rsp,%rbp
400603:  mov  %rax,%rdx
400606:  shr  $0x3f,%rdx
40060a:  add  %rdx,%rax
40060d:  sar  %rax
400610:  jne  400614
400612:  pop  %rbp
400613:  retq
```

void call_echo() {
  echo();
}

“Returns” to unrelated code
Lots of things happen, without modifying critical state
Eventually executes retq back to main – call_echo has no local variables
Stack Smashing Attacks

- Overwrite normal return address A with address of some other code S
- When Q executes `ret`, will jump to other code

```c
int Q() {
    char buf[64];
    gets(buf);
    ...
    return ...;
}
```

```c
void S() {
    /* Something unexpected */
    ...
}
```

```c
void P() {
    Q();
    ...
}
```

Stack after call to `gets()`

- P stack frame
- Q stack frame
- Data written by `gets()`
- Return address A

Crafting Smashing String

Stack Frame for call echo

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int echo() {
  char buf[4];
  gets(buf);
  ...
  return ...;
}

%rsp

Target Code

void smash() {
  printf("I've been smashed!\n");
  exit(0);
}

00000000004008a3 <smash>:
  4008a3:  48 83 ec 08

Attack String (Hex)

30 31 32 33 34 35 36 37 38 39 30 31 32 33 34 35 36 37 38 39 30 31 32 33
a3 08 40 00 00 00 00 00 00
Smashing String Effect

Stack Frame for call echo

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%rsp

Target Code

```c
void smash() {
    printf("I've been smashed!\n");
    exit(0);
}
```

Attack String (Hex)

```
30 31 32 33 34 35 36 37 38 39 30 31 32 33 34 35 36 37 38 39 30 31 32 33
a3 08 40 00 00 00 00 00
```

```
00000000004008a3 <smash>: 48 83 ec 08
```
Code Injection Attacks

Input string contains byte representation of executable code

Overwrite return address A with address of buffer B

When Q executes `return`, will jump to exploit code
How Does The Attack Code Execute?

```c
void P()
{
  Q();
  ...
}

int Q()
{
  char buf[64];
  gets(buf); // A->B
  ...
  return ...;
}
```
What To Do About Buffer Overflow Attacks

- Avoid overflow vulnerabilities
- Employ system-level protections
- Have compiler use “stack canaries”

- Lets talk about each...
1. Avoid Overflow Vulnerabilities in Code (!)

```c
/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    fgets(buf, 4, stdin);
    puts(buf);
}
```

- For example, use library routines that limit string lengths
  - `fgets` instead of `gets`
  - `strncpy` instead of `strcpy`
  - Don’t use `scanf` with `%s` conversion specification
    - Use `fgets` to read the string
    - Or use `%ns` where `n` is a suitable integer
2. System-Level Protections can help

- **Randomized stack offsets**
  - At start of program, allocate random amount of space on stack
  - Shifts stack addresses for entire program
  - Makes it difficult for hacker to predict beginning of inserted code
  - E.g.: 5 executions of memory allocation code
    - Stack repositioned each time program executes

```
local 0x7ffe4d3be87c 0x7fff75a4f9fc 0x7ffeadb7c80c 0x7ffeaea2fdac 0x7ffcd452017c
```
2. System-Level Protections can help

- Nonexecutable code segments
  - In traditional x86, can mark region of memory as either “read-only” or “writeable”
  - Can execute anything readable
  - x86-64 added explicit “execute” permission
  - Stack marked as non-executable

Any attempt to execute this code will fail
3. Stack Canaries can help

- **Idea**
  - Place special value ("canary") on stack just beyond buffer
  - Check for corruption before exiting function

- **GCC Implementation**
  - `-fstack-protector`
  - Now the default (disabled earlier)

```
unix>./bufdemo-sp
Type a string:0123456
0123456

unix>./bufdemo-sp
Type a string:01234567
*** stack smashing detected ***
```
Protected Buffer Disassembly

```assembly
40072f:  sub    $0x18,%rsp
400733:  mov    %fs:0x28,%rax
40073c:  mov    %rax,0x8(%rsp)
400741:  xor    %eax,%eax
400743:  mov    %rsp,%rdi
400746:  callq  4006e0 <gets>
40074b:  mov    %rsp,%rdi
40074e:  callq  400570 <puts@plt>
400753:  mov    0x8(%rsp),%rax
400758:  xor    %fs:0x28,%rax
400761:  je     400768 <echo+0x39>
400763:  callq  400580 __stack_chk_fail@plt>
400768:  add    $0x18,%rsp
40076c:  retq
```
Setting Up Canary

Before call to gets

```
/* Echo Line */
void echo()
{
    char buf[4]; /* Way too small! */
    gets(buf);
    puts(buf);
}
```

**Stack Frame for call_echo**

<table>
<thead>
<tr>
<th>Return Address (8 bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canary (8 bytes)</td>
</tr>
<tr>
<td>[3] [2] [1] [0]</td>
</tr>
</tbody>
</table>

buf ← %rsp

echo:

```
...  
movq   %fs:40, %rax   # Get canary
movq   %rax, 8(%rsp)  # Place on stack
xorl   %eax, %eax    # Erase canary
...  
```
Checking Canary

After call to gets

```c
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

Input: 0123456

After call to gets

```
echo:
   ... 
   movq  8(%rsp), %rax  # Retrieve from stack
   xorq  %fs:40, %rax   # Compare to canary
   je    .L6           # If same, OK
   call  __stack_chk_fail # FAIL
```
Return-Oriented Programming Attacks

- **Challenge (for hackers)**
  - Stack randomization makes it hard to predict buffer location
  - Marking stack nonexecutable makes it hard to insert binary code

- **Alternative Strategy**
  - Use existing code
    - E.g., library code from stdlib
  - String together fragments to achieve overall desired outcome
  - *Does not overcome stack canaries*

- **Construct program from gadgets**
  - Sequence of instructions ending in `ret`
    - Encoded by single byte `0xc3`
  - Code positions fixed from run to run
  - Code is executable
Gadget Example #1

```c
long ab_plus_c(long a, long b, long c) {
    return a*b + c;
}
```

00000000004004d0 <ab_plus_c>:
4004d0:  48 0f af fe  imul %rsi,%rdi
4004d4:  48 8d 04 17  lea (%rdi,%rdx,1),%rax
4004d8:  c3           retq

rax ← rdi + rdx
Gadget address = 0x4004d4

- Use tail end of existing functions
Gadget Example #2

```c
void setval(unsigned *p) {
  *p = 3347663060u;
}
```

Gadget address = 0x4004dc

Repurpose byte codes
ROP Execution

- **Trigger with `ret` instruction**
  - Will start executing Gadget 1

- **Final `ret` in each gadget will start next one**
Crafting an ROB Attack String

Stack Frame for call echo

<table>
<thead>
<tr>
<th>RBP</th>
<th>RBX</th>
<th>RSI</th>
<th>RDI</th>
<th>RDX</th>
<th>EBP</th>
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<td>36</td>
<td>35</td>
<td>34</td>
<td>33</td>
<td>32</td>
</tr>
</tbody>
</table>

Gadget

rax ← rdi + rdx

000000000004004d0 <ab_plus_c>:
4004d0: 48 0f af fe imul %rsi,%rdi
4004d4: 48 8d 04 17 lea (%rdi,%rdx,1),%rax
4004d8: c3

Return Address (8 bytes)

00 00 00 00

%rax

Attack String (Hex)

30 31 32 33 34 35 36 37 38 39 30 31 32 33 34 35 36 37 38 39 30 31 32 33
d4 04 40 00 00 00 00 00

Multiple gadgets will corrupt stack upwards
Today

- Memory Layout
- Buffer Overflow
  - Vulnerability
  - Protection
- Unions
Union Allocation

- Allocate according to largest element
- Can only use one field at a time

union U1 {
    char c;
    int i[2];
    double v;
} *up;

struct S1 {
    char c;
    int i[2];
    double v;
} *sp;
Using Union to Access Bit Patterns

typedef union {
    float f;
    unsigned u;
} bit_float_t;

float bit2float(unsigned u) {
    bit_float_t arg;
    arg.u = u;
    return arg.f;
}

unsigned float2bit(float f) {
    bit_float_t arg;
    arg.f = f;
    return arg.u;
}

Same as (float) u?  
Same as (unsigned) f?
Byte Ordering Revisited

■ Idea
  ▪ Short/long/quad words stored in memory as 2/4/8 consecutive bytes
  ▪ Which byte is most (least) significant?
  ▪ Can cause problems when exchanging binary data between machines

■ Big Endian
  ▪ Most significant byte has lowest address
  ▪ Sparc, Internet

■ Little Endian
  ▪ Least significant byte has lowest address
  ▪ Intel x86, ARM Android and IOS

■ Bi Endian
  ▪ Can be configured either way
  ▪ ARM
### Byte Ordering Example

```c
union {
    unsigned char c[8];
    unsigned short s[4];
    unsigned int i[2];
    unsigned long l[1];
} dw;
```

How are the bytes inside short/int/long stored?

#### Memory addresses growing

**32-bit**

<table>
<thead>
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<tbody>
<tr>
<td>i[0]</td>
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<td>i[1]</td>
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<td></td>
<td></td>
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<tr>
<td>l[0]</td>
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</tbody>
</table>

**64-bit**

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</tr>
</tbody>
</table>
Byte Ordering Example (Cont).

```c
int j;
for (j = 0; j < 8; j++)
    dw.c[j] = 0xf0 + j;

printf("Characters 0-7 == [0x%x,0x%x,0x%x,0x%x,  
    0x%x,0x%x,0x%x,0x%x]\n",
    dw.c[0], dw.c[1], dw.c[2], dw.c[3],
    dw.c[4], dw.c[5], dw.c[6], dw.c[7]);

printf("Shorts 0-3 == [0x%x,0x%x,0x%x,0x%x]\n",
    dw.s[0], dw.s[1], dw.s[2], dw.s[3]);

printf("Ints 0-1 == [0x%x,0x%x]\n",
    dw.i[0], dw.i[1]);

printf("Long 0 == [0x%lx]\n",
    dw.l[0]);
```
# Byte Ordering on IA32

## Little Endian

<table>
<thead>
<tr>
<th>f0</th>
<th>f1</th>
<th>f2</th>
<th>f3</th>
<th>f4</th>
<th>f5</th>
<th>f6</th>
<th>f7</th>
</tr>
</thead>
<tbody>
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</tr>
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</table>

**Print**

## Output:

- **Characters** 0–7 == \([0xf0, 0xf1, 0xf2, 0xf3, 0xf4, 0xf5, 0xf6, 0xf7]\)
- **Shorts** 0–3 == \([0xf1f0, 0xf3f2, 0xf5f4, 0xf7f6]\)
- **Ints** 0–1 == \([0xf3f2f1f0, 0xf7f6f5f4]\)
- **Long** 0 == \([0xf3f2f1f0]\)
## Byte Ordering on Sun

### Big Endian

<table>
<thead>
<tr>
<th>f0</th>
<th>f1</th>
<th>f2</th>
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</tbody>
</table>

Output on Sun:

- **Characters** 0-7 == \([0xf0, 0xf1, 0xf2, 0xf3, 0xf4, 0xf5, 0xf6, 0xf7]\)
- **Shorts** 0-3 == \([0xf0f1, 0xf2f3, 0xf4f5, 0xf6f7]\)
- **Ints** 0-1 == \([0xf0f1f2f3, 0xf4f5f6f7]\)
- **Long** 0 == \([0xf0f1f2f3]\)
Byte Ordering on x86-64

Little Endian

<table>
<thead>
<tr>
<th>f0</th>
<th>f1</th>
<th>f2</th>
<th>f3</th>
<th>f4</th>
<th>f5</th>
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<th>f7</th>
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Output on x86-64:

- Characters 0-7 == [0xf0, 0xf1, 0xf2, 0xf3, 0xf4, 0xf5, 0xf6, 0xf7]
- Shorts 0-3 == [0xf1f0, 0xf3f2, 0xf5f4, 0xf7f6]
- Ints 0-1 == [0xf3f2f1f0, 0xf7f6f5f4]
- Long 0 == [0xf7f6f5f4f3f2f1f0]
Summary of Compound Types in C

- **Arrays**
  - Contiguous allocation of memory
  - Aligned to satisfy every element’s alignment requirement
  - Pointer to first element
  - No bounds checking

- **Structures**
  - Allocate bytes in order declared
  - Pad in middle and at end to satisfy alignment

- **Unions**
  - Overlay declarations
  - Way to circumvent type system
Summary

- Memory Layout
- Buffer Overflow
  - Vulnerability
  - Protection
  - Code Injection Attack
  - Return Oriented Programming
- Unions
Exploits Based on Buffer Overflows

- **Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines**

- Distressingly common in real programs
  - Programmers keep making the same mistakes 😞
  - Recent measures make these attacks much more difficult

- **Examples across the decades**
  - Original “Internet worm” (1988)
  - “IM wars” (1999)
  - Twilight hack on Wii (2000s)
  - ... and many, many more

- **You will learn some of the tricks in attacklab**
  - Hopefully to convince you to never leave such holes in your programs!!
Example: the original Internet worm (1988)

- Exploited a few vulnerabilities to spread
  - Early versions of the finger server (fingerd) used `gets()` to read the argument sent by the client:
    - `finger droh@cs.cmu.edu`
  - Worm attacked fingerd server by sending phony argument:
    - `finger "exploit-code padding new-return-address"
    - exploit code: executed a root shell on the victim machine with a direct TCP connection to the attacker.

- Once on a machine, scanned for other machines to attack
  - invaded ~6000 computers in hours (10% of the Internet 😊)
    - see June 1989 article in *Comm. of the ACM*
  - the young author of the worm was prosecuted...
  - and CERT was formed... still homed at CMU
Example 2: IM War

- July, 1999
  - Microsoft launches MSN Messenger (instant messaging system).
  - Messenger clients can access popular AOL Instant Messaging Service (AIM) servers

![Diagram showing the relationship between MSN server, MSN client, AIM server, and AIM clients.]
IM War (cont.)

August 1999

- Mysteriously, Messenger clients can no longer access AIM servers
- Microsoft and AOL begin the IM war:
  - AOL changes server to disallow Messenger clients
  - Microsoft makes changes to clients to defeat AOL changes
  - At least 13 such skirmishes
- What was really happening?
  - AOL had discovered a buffer overflow bug in their own AIM clients
  - They exploited it to detect and block Microsoft: the exploit code returned a 4-byte signature (the bytes at some location in the AIM client) to server
  - When Microsoft changed code to match signature, AOL changed signature location
Date: Wed, 11 Aug 1999 11:30:57 -0700 (PDT)
From: Phil Bucking <philbucking@yahoo.com>
Subject: AOL exploiting buffer overrun bug in their own software!
To: rms@pharlap.com

Mr. Smith,

I am writing you because I have discovered something that I think you might find interesting because you are an Internet security expert with experience in this area. I have also tried to contact AOL but received no response.

I am a developer who has been working on a revolutionary new instant messaging client that should be released later this year.

... It appears that the AIM client has a buffer overrun bug. By itself this might not be the end of the world, as MS surely has had its share. But AOL is now *exploiting their own buffer overrun bug* to help in its efforts to block MS Instant Messenger.

... Since you have significant credibility with the press I hope that you can use this information to help inform people that behind AOL's friendly exterior they are nefariously compromising peoples' security.

Sincerely,
Phil Bucking
Founder, Bucking Consulting
philbucking@yahoo.com

*It was later determined that this email originated from within Microsoft!*
Aside: Worms and Viruses

- **Worm: A program that**
  - Can run by itself
  - Can propagate a fully working version of itself to other computers

- **Virus: Code that**
  - Adds itself to other programs
  - Does not run independently

- **Both are (usually) designed to spread among computers and to wreak havoc**