Machine-Level Programming V: Advanced Topics

15-213: Introduction to Computer Systems
9th Lecture, Sep. 29, 2015

Instructors:
Randal E. Bryant and David R. O’Hallaron
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: 00007FFFFFFFFFFFFFFF

Diagram:

- Stack
- Heap
- Data
- Shared Libraries
- Text
- Executable machine instructions
- Read-only
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?

Bryant and O'Hallaron, Computer Systems: A Programmer’s Perspective, Third Edition
x86-64 Example Addresses

address range $\sim 2^{47}$

local
p1
p3
p4
p2
big_array
huge_array
main()
useless()

0x00007ffe4d3be87c
0x00007f7262a1e010
0x00007f7162a1d010
0x000000008359d120
0x000000008359d010
0x0000000080601060
0x0000000000601060
0x00000000000040060c
0x000000000000400590

not drawn to scale
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:

<table>
<thead>
<tr>
<th>Critical State</th>
<th>Location accessed by fun(i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td></td>
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<tr>
<td>5</td>
<td></td>
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<tr>
<td>4</td>
<td></td>
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<td>3</td>
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<td>1</td>
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<tr>
<td>0</td>
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</tr>
</tbody>
</table>

struct_t
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();
}
```

btw, how big is big enough?

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

```bash
unix> ./bufdemo-nsp
Type a string: 0123456789012345678901234
Segmentation Fault
```
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 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);
}
Buffer Overflow Stack Example

Before call to gets

Stack Frame for call_echo

<table>
<thead>
<tr>
<th>00</th>
<th>00</th>
<th>00</th>
<th>00</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>40</td>
<td>06</td>
<td>f6</td>
</tr>
</tbody>
</table>

20 bytes unused

buf ← %rsp

```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
. . .
```
Buffer Overflow Stack Example #1

After call to gets

Stack Frame for call_echo

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

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

#### After call to `gets`

| Stack Frame for `call_echo` | void echo() { \n| | char buf[4]; \n| | gets(buf); \n| | ... \n| | } \n| echo: \n| | subq $24, %rsp \n| | movq %rsp, %rdi \n| | call gets \n| | ... \n
#### `call_echo`:

- `4006f6:  add  $0x8,%rsp`  

buf ← %rsp

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

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

<table>
<thead>
<tr>
<th>00</th>
<th>00</th>
<th>00</th>
<th>00</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>40</td>
<td>06</td>
<td>00</td>
</tr>
<tr>
<td>33</td>
<td>32</td>
<td>31</td>
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<td>31</td>
<td>30</td>
<td>39</td>
<td>38</td>
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<tr>
<td>37</td>
<td>36</td>
<td>35</td>
<td>34</td>
</tr>
<tr>
<td>33</td>
<td>32</td>
<td>31</td>
<td>30</td>
</tr>
</tbody>
</table>

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
```

buf ← %rsp

“Returns” to unrelated code
Lots of things happen, without modifying critical state
Eventually executes retq back to main
Code Injection Attacks

Input string contains byte representation of executable code
Overwrite return address A with address of buffer B
When Q executes `ret`, will jump to exploit code
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
**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
OK, 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

```
l0cal 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

**echo:**

<table>
<thead>
<tr>
<th>Address</th>
<th>Opcode</th>
<th>Machine Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>40072f</td>
<td>sub</td>
<td>$0x18,%rsp</td>
</tr>
<tr>
<td>400733</td>
<td>mov</td>
<td>%fs:0x28,%rax</td>
</tr>
<tr>
<td>40073c</td>
<td>mov</td>
<td>%rax,0x8(%rsp)</td>
</tr>
<tr>
<td>400741</td>
<td>xor</td>
<td>%eax,%eax</td>
</tr>
<tr>
<td>400743</td>
<td>mov</td>
<td>%rsp,%rdi</td>
</tr>
<tr>
<td>400746</td>
<td>callq</td>
<td>4006e0 &lt;gets&gt;</td>
</tr>
<tr>
<td>40074b</td>
<td>mov</td>
<td>%rsp,%rdi</td>
</tr>
<tr>
<td>40074e</td>
<td>callq</td>
<td>400570 <a href="mailto:puts@plt">puts@plt</a></td>
</tr>
<tr>
<td>400753</td>
<td>mov</td>
<td>0x8(%rsp),%rax</td>
</tr>
<tr>
<td>400758</td>
<td>xor</td>
<td>%fs:0x28,%rax</td>
</tr>
<tr>
<td>400761</td>
<td>je</td>
<td>400768 &lt;echo+0x39&gt;</td>
</tr>
<tr>
<td>400763</td>
<td>callq</td>
<td>400580 __stack_chk_fail@plt</td>
</tr>
<tr>
<td>400768</td>
<td>add</td>
<td>$0x18,%rsp</td>
</tr>
<tr>
<td>40076c</td>
<td>retq</td>
<td></td>
</tr>
</tbody>
</table>
Setting Up Canary

Before call to gets

Stack Frame for call_echo

Return Address (8 bytes)

Canary (8 bytes)

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`

<table>
<thead>
<tr>
<th>Stack Frame for <code>call_echo</code></th>
<th>Return Address (8 bytes)</th>
<th>Canary (8 bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>00 36 35 34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>33 32 31 30</td>
</tr>
</tbody>
</table>

Input: **0123456**

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

```
// Output:
... buf ← %rsp

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
.L6:    ...  
```
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

```
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
Repurpose byte codes
ROP Execution

- **Trigger with ret instruction**
  - Will start executing Gadget 1
- **Final ret in each gadget will start next one**
Today

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

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

```c
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

■ 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;
```

### 32-bit

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>s[0]</td>
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<td>i[1]</td>
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<td>l[0]</td>
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### 64-bit

<table>
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<tbody>
<tr>
<td>s[0]</td>
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<td>s[1]</td>
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<td>s[2]</td>
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<td>s[3]</td>
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<td>i[0]</td>
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<tr>
<td>i[1]</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>l[0]</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</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>
</table>

LSB  MSB  LSB  MSB

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></th>
<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>
<tr>
<td></td>
<td>i[0]</td>
<td></td>
<td></td>
<td></td>
<td>i[1]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>l[0]</td>
<td></td>
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<td></td>
<td></td>
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</tr>
</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>
<th>f6</th>
<th>f7</th>
</tr>
</thead>
<tbody>
<tr>
<td>i[0]</td>
<td></td>
<td></td>
<td></td>
<td>i[1]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>l[0]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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