

CSCI 2021: x86-64 Assembly Extras and Wrap

Chris Kauffman

*Last Updated:
Tue Oct 17 03:14:30 PM EDT 2023*

Logistics

Announcements

Reminders of Techniques for Puzzlebin

GDB Tricks from Quick Guide to GDB

Command	Effect
<code>break *0x1248f2</code>	Break at specific instruction address
<code>break *func+24</code>	Break at instruction with decimal offset from a label
<code>break *func+0x18</code>	Break at instruction with hex offset from a label
<code>x \$rax</code>	Print memory pointed to by register rax
<code>x /gx \$rax</code>	Print as "giant" 64-bit numbers in hexadecimal format
<code>x /5gd \$rax</code>	Print 5 64-bit numbers starting where rax points in decimal format

Disassembling Binaries: `objdump -d prog > code.txt`

```
>> objdump -d a.out                                # DISASSEMBLE BINARY
0000000000000119 <main>:
    1119:    48 c7 c0 00 00 00 00    mov     $0x0,%rax
    1120:    48 c7 c1 01 00 00 00    mov     $0x1,%rcx
    1127:    48 c7 c2 64 00 00 00    mov     $0x64,%rdx
0000000000000112e <LOOP>:
    112e:    48 39 d1                cmp     %rdx,%rcx
    1131:    7f 08                  jg      113b <END>
    1133:    48 01 c8                add     %rcx,%rax
...
>> objdump -d a.out > code.txt # STORE RESULTS IN FILE
```

Exercise: All Models are Wrong...

- ▶ Rule #1: The Doctor Lies
- ▶ Below is our original model for memory layout of C programs
- ▶ Describe what is **incorrect** based on x86-64 assembly
- ▶ What is **actually** in the stack? How are registers likely used?

```
9: int main(...){
10:   int x = 19;
11:   int y = 31;
+<-12: swap(&x, &y);
| 13:   printf("%d %d\n",x,y);
| 14:   return 0;
V 15: }
```

STACK: Caller main(), prior to swap()

FRAME	ADDR	NAME	VALUE
-----+-----+-----+-----			
main()	#2048	x	19
line:12	#2044	y	31
-----+-----+-----+-----			

```
|
| 18: void swap(int *a,int *b){
+>-19:   int tmp = *a;
20:   *a = *b;
21:   *b = tmp;
22:   return;
23: }
```

STACK: Callee swap() takes control

FRAME	ADDR	NAME	VALUE	
-----+-----+-----+-----				
main()	#2048	x	19	<-+
line:12	#2044	y	31	<- +
-----+-----+-----+-----				
swap()	#2036	a	#2048	---+
line:19	#2028	b	#2044	----+
	#2024	tmp	?	

Answers: All Models are Wrong, Some are Useful

```

    9: int main(...){
    10:   int x = 19;
    11:   int y = 31;
+<-12:   swap(&x, &y);
|  13:   printf("%d %d\n",x,y);
|  14:   return 0;
V 15: }
|
|  18: void swap(int *a,int *b){
+>-19:   int tmp = *a;
    20:   *a = *b;
    21:   *b = tmp;
    22:   return;
    23: }
```

```

STACK: Callee swap() takes control
| FRAME   | ADDR   | NAME  | VALUE |
|-----+-----+-----+-----|
| main()  | #2048  | x     | 19    |
|         | #2044  | y     | 31    |
|-----+-----+-----+-----|
| swap()  | #2036  | rip   | Line 13|
|-----+-----+-----+-----|
```

```

REGS as swap() starts
| REG | VALUE | NOTE |
|-----+-----+-----|
| rdi | #2048 | for *a |
| rsi | #2044 | for *b |
| rax | ?     | for tmp |
| rip | L19   | line in swap |
```

- ▶ `main()` must have stack space for locals passed by address
- ▶ `swap()` needs no stack space for arguments: in registers
- ▶ Return address is next value of `rip` register in `main()`
- ▶ Mostly don't need to think at this level of detail but **can be useful in some situations**

Accessing Global Variables in Assembly

Global data can be set up in assembly in `.data` sections with labels and assembler directives like `.int` and `.short`

```
.data
an_int:          # single int
                .int 17
some_shorts:     # array of shorts
                .short 10 # some_shorts[0]
                .short 12 # some_shorts[1]
                .short 14 # some_shorts[2]
```

Modern Access to Globals

```
movl an_int(%rip), %eax
leaq some_shorts(%rip), %rdi
```

- ▶ Uses `%rip` relative addressing
- ▶ Default in `gcc` as it plays nice with OS security features
- ▶ May discuss again later during Linking/ELF coverage

Traditional Access to Globals

```
movl an_int, %eax      # ERROR
leaq (some_shorts), %rdi # ERROR
```

- ▶ Not accepted by `gcc` by default
- ▶ Yields compile/link errors

```
/usr/bin/ld: /tmp/ccocSiv5.o:
relocation R_X86_64_32S against `'.data'
can not be used when making a PIE object;
recompile with -fPIE
```

Aggregate Data In Assembly (Arrays + Structs)

Arrays

Usually: $\text{base} + \text{index} \times \text{size}$

```
arr[i] = 12;
```

```
movl $12, (%rdi,%rsi,4)
```

```
int x = arr[j];
```

```
movl (%rdi,%rcx,4), %r8d
```

- ▶ Array starting address often held in a register
- ▶ Index often in a register
- ▶ Compiler inserts appropriate size (1,2,4,8)

Structs

Usually $\text{base} + \text{offset}$

```
typedef struct {  
    int i; short s;  
    char c[2];
```

```
} foo_t;
```

```
foo_t *f = ...;
```

```
short sh = f->s;
```

```
movw 4(%rdi), %si
```

```
f->c[i] = 'X';
```

```
movb $88, 6(%rdi,%rax)
```


Packed Structures as Procedure Arguments

- ▶ Passing pointers to structs is 'normal': registers contain addresses to main memory
- ▶ Passing actual structs may result in *packed structs* where several fields are in a single register
- ▶ Assembly must *unpack* these through **shifts and masking**

```
1 // packed_struct_main.c
2 typedef struct {
3     short first;
4     short second;
5 } twoshort_t;
6
7 short sub_struct(twoshort_t ti);
8
9 int main(){
10     twoshort_t ts = {.first=10,
11                     .second=-2};
12     int sum = sub_struct(ts);
13     printf("%d - %d = %d\n",
14           ts.first, ts.second, sum);
15     return 0;
16 }
```

```
1 ### packed_struct.s
2 .text
3 .globl sub_struct
4 sub_struct:
5     ## first arg is twoshort_t ts
6     ## %rdi has 2 packed shorts in it
7     ## bits 0-15 are ts.first
8     ## bits 16-31 are ts.second
9     ## upper bits could be anything
10
11     movl %edi,%eax    # eax = ts;
12     andl $0xFFFF,%eax # eax = ts.first;
13     sarl $16,%edi     # edi = edi >> 16;
14     andl $0xFFFF,%edi # edi = ts.second;
15     subw %di,%ax      # ax = ax - di
16     ret              # answer in ax
```

Example: coins_t in HW06 / Lab07

```
// Type for collections of coins
typedef struct { // coin_t has the following memory layout
    char quarters; //
    char dimes;    // |           | Pointer | Packed | Packed |
    char nickels;  // |           | Memory | Struct | Struct |
    char pennies;  // | Field   | Offset | Arg#   | Bits   |
} coins_t;        // |-----+-----+-----+-----|
                  // | quarters | +0 | #1    | 0-7    |
                  // | dimes   | +1 | #1    | 8-15   |
                  // | nickels | +2 | #1    | 16-23  |
                  // | pennies | +3 | #1    | 24-31  |
```

```
## | #2048 | c->quarters | 2 |
## | #2049 | c->dimes      | 1 |
## | #2050 | c->nickels   | - |
## | #2051 | c->pennies   | - |
```

```
set_coins:
### int set_coins(int cents, coins_t *coins)
### %edi = int cents
### %rsi = coins_t *coins
...
# rsi: #2048
# al: 0 %dl: 3
movb    %al,2(%rsi)    # coins->nickels = al;
movb    %dl,3(%rsi)    # coins->pennies = dl;
```

```
## | #2048 | c->quarters | 2 |
## | #2049 | c->dimes      | 1 |
## | #2050 | c->nickels   | 0 |
## | #2051 | c->pennies   | 3 |
```

```
total_coins:
### args are
### %rdi packed coin_t struct with struct fields
### { 0- 7: quarters, 8-15: dimes,
###   16-23: nickels, 24-31: pennies}
```

...

```
### rdi: 0x00 00 00 00 03 00 01 02
###                                     p n d q
    movq    %rdi,%rdx                # extract dimes
### rdx: 0x00 00 00 00 03 00 01 02
###                                     p n d q
    sarq    $8,%rdx                  # shift dimes to low bits
### rdx: 0x00 00 00 00 00 03 00 01
###                                     p n d
    andq    $0xFF,%rdx               # rdx = dimes
### rdx: 0x00 00 00 00 00 00 00 01
###                                     p n d
```

Large Packed Structs

- ▶ Large structs that don't fit into single registers may be packed across several argument registers
- ▶ This is the case in P3

```
typedef struct{  
    int    day_secs;    // 4  
    short  time_secs;   // 2  
    short  time_mins;   // 2  
    short  time_hours;  // 2  
    char   ampm;        // 1+1 pad  
} tod_t;               // 12 bytes
```

```
int set_display_from_tod(tod_t tod, ...)  
// ~~~ Large packed struct
```

C Field Access	Register	Bits in reg	Shift Required	Size
tod.day_secs	%rdi	0-31	None	4 bytes
tod.time_secs	%rdi	32-47	Right by 32	2 bytes
tod.time_mins	%rdi	48-63	Right by 48	2 bytes
tod.time_hours	%rsi	0-15	None	2 bytes
tod.ampm	%rsi	16-23	Right by 16	1 bytes

General Cautions on Structs

Struct Layout by Compilers

- ▶ Compiler honors order of source code fields in struct
- ▶ BUT compiler may add padding between/after fields for alignment
- ▶ Compiler determines total struct size

Struct Layout Algorithms

- ▶ Baked into compiler
- ▶ **May change from compiler to compiler**
- ▶ May change through history of compiler

Structs in Mem/Regs

- ▶ Local var structs spread across several registers
- ▶ Don't need a struct on the stack at all in some cases (just like don't need local variables on stack)
- ▶ Struct arguments packed into 1+ registers

Stay Insulated

- ▶ Programming in C insulates you from all of this
- ▶ Feel the **warmth** of gcc's abstraction blanket

Security Risks in C

Buffer Overflow Attacks

- ▶ No default bounds checking in C: Performance favored over safety
- ▶ Allows classic security flaws:

```
char buf[1024];  
printf("Enter you name:");  
fscanf(file,"%s",buf); // BAD  
// or  
gets(buf); // BAD  
// my name is 1500 chars  
// long, what happens?
```

- ▶ For data larger than buf, begin overwriting other parts of the stack
 - ▶ Clobber return addresses
 - ▶ Insert executable code and run it

Counter-measures

- ▶ **Stack protection** is default in gcc in the modern era
- ▶ Inserts “canary” values on the stack near return address
- ▶ Prior to function return, checks that canaries are unchanged
- ▶ **Stack / Text Section Start randomized** by kernel, return address and function addresses difficult to predict ahead of time
- ▶ Kernel may also vary virtual memory address as well
- ▶ Disabling protections is risky

Stack Smashing

- ▶ Explored in a recent homework
- ▶ See `stack_smash.c` for a similar example
- ▶ Demonstrates detection of changes to stack that could be harmful / security threat

```
// stack_smash.c
void demo(){
    int arr[4];    // fill array off the end
    for(int i=0; i<8; i++){
        arr[i] = (i+1)*2;
    }

    for(int i=0; i<8; i++){
        printf("[%d]: %d\n",i,arr[i]);
    }
}

int main(){
    printf("About to do the demo\n");
    demo();
    printf("Demo Complete\n");
    return 0;
}
```

```
> cd 08-assembly-extras-code/
> gcc stack_smash1.c
> ./a.out
About to do the demo
[0]: 2
[1]: 4
[2]: 6
...
[7]: 16
*** stack smashing detected ***:
terminated
Aborted (core dumped)
```

Demonstration of Buffer Overflow Attack

- ▶ See the code `buffer_overflow.c`
- ▶ Presents an easier case to demo stack manipulations
- ▶ Prints addresses of functions `main()` and `never()`
- ▶ Reads long values which are 64-bits, easier to line up data in stack than with strings; still overflowing the buffer by reading too much data as in:

```
void always(){  
    long buf[1] = {0xABCD};           // room for 1  
    ...  
    printf("Enter 4 hex values: ");  
    fscanf(stdin,"%lx %lx %lx %lx", // reads 4  
           &buf[0], &buf[1], &buf[2], &buf[3]);
```

- ▶ When compiled via

```
>> gcc -fno-stack-protector buffer_overflow.c
```

can get `never()` to run by entering its address as input which will overwrite the return address

Sample Buffer Overflow Code

```
#include <stdio.h>
void print_all_passwords(){
    ...
}
int main(){
    printf("file to open: ");
    char buf[128];
    fscanf(stdin,"%s",buf);
    printf("You entered: %s\n",buf);

    ...;
    return 0;
    // By entering the correct length of string followed by the ASCII
    // representation of the address of print_all_passwords(), one might
    // be able to get that function when "return" is reached if there
    // are no stack protection mechanisms at work ...
    // (which was the case in 1999 on Windows :-)
```

```
}
```


Details of GCC / Linux Stack Security

- ▶ Programs compiled with GCC + Glibc on Linux for x86-64 will default to having stack protection
- ▶ This can be seen in compiled code as short blocks near the beginning and end of functions which
 1. At the beginning of the function uses an instruction like `movq %fs:40, %rax` and places a value in the stack beneath the return address
 2. At the end of the function again accesses `%fs:40` and the value earlier placed in the stack.
- ▶ The `%fs` register is a special **segment register** originally introduced in the 16-bit era to surmount memory addressing limitations; now used only for limited purposes
- ▶ The complete details are beyond the scope of our course BUT
- ▶ **A somewhat detailed explanation has been added to**
`08-assembly-extras-code/stack_protect.org`

Floating Point Operations

- ▶ Original Intel 8086 Processor **didn't do floating point ops**
- ▶ Had to buy a co-processor (Intel 8087) to enable FP ops
- ▶ Most modern CPUs support FP ops but they feel separate from the integer ops: FPU versus ALU

x86-64 “Media” Registers

512	256	128-bits	Use
%xmm0	%ymm0	%xmm0	FP Arg1/Ret
%xmm1	%ymm1	%xmm1	FP Arg2
...
%xmm7	%ymm7	%xmm7	FP Arg 8
%xmm8	%ymm8	%xmm8	Caller Save
...
%xmm15	%ymm15	%xmm15	Caller Save

- ▶ Can be used as “scalars” - single values but...
- ▶ `xmmI` is 128 bits big holding
 - ▶ 2 \times 64-bit double's OR
 - ▶ 4 \times 32-bit float's
- ▶ `ymmI` / `zmmI` extend further

Instructions

```
vaddss %xmm2,%xmm4,%xmm0
# xmm0[0] = xmm2[0] + xmm4[0]
# Add Scalar Single-Precision
```

```
vaddps %xmm2,%xmm4,%xmm0
# xmm0[:] = xmm2[:] + xmm4[:]
# Add Packed Single-Precision
# "Vector" Instruction
```

- ▶ Operates on single values or “vectors” of packed values
- ▶ 3-operands common in more “modern” assembly languages

Example: float_ops.c to Assembly

```
// float_ops.c: original C Code
```

```
void array_add(float *arr1, float *arr2, int len){  
    for(int i=0; i<len; i++){  
        arr1[i] += arr2[i];  
    }  
}
```

```
# >> gcc -S -Og float_ops.c
```

```
# Minimal optimizations
```

```
array_add:    ## 16 lines asm
```

```
.LFB0:
```

```
.cfi_startproc
```

```
movl $0, %eax
```

```
jmp .L2
```

```
.L3:
```

```
movslq %eax, %r8
```

```
leaq (%rdi,%r8,4), %rcx
```

```
movss (%rsi,%r8,4), %xmm0
```

```
addss (%rcx), %xmm0    ## add single
```

```
movss %xmm0, (%rcx)    ## single prec
```

```
addl $1, %eax
```

```
.L2:
```

```
cmpl %edx, %eax
```

```
jle .L3
```

```
ret
```

```
# >> gcc -S -O3 -mavx float_ops.c
```

```
# Max optimizations, Use AVX hardware
```

```
array_add:    ## 100 lines asm
```

```
...
```

```
.L5:          ## vector move/adds
```

```
vmovups (%rcx,%rdx), %ymm1
```

```
vaddps (%rsi,%rdx), %ymm1, %ymm0
```

```
vmovups %ymm0, (%rcx,%rdx)
```

```
addq $32, %rdx
```

```
cmpq %rdi, %rdx
```

```
jne .L5
```

```
...
```

```
.L9:          ## single move/adds
```

```
vmovss (%rcx,%rax), %xmm0
```

```
vaddss (%rsi,%rax), %xmm0, %xmm0
```

```
vmovss %xmm0, (%rcx,%rax)
```

```
addq $4, %rax
```

```
cmpq %rax, %rdx
```

```
jne .L9
```

```
ret
```

Floating Point and ALU Conversions

- ▶ Recall that bit layout of Integers and Floating Point numbers are quite different (**how?**)
- ▶ Leads to a series of assembly instructions to interconvert between types

```
# file:float_convert.c
```

```
# int eax = ...;  
# double xmm0 = (double) eax;  
cvtsi2sdl    %eax, %xmm0
```

```
# double xmm1 = ...  
# long rcx = (long) xmm1;  
cvttsd2siq   %xmm0, %rax
```

- ▶ These are non-trivial conversions: 5-cycle latency (delay) before completion, can have a performance impact on code which does conversions