CSE 351 Midterm Exam

Winter 2019

Thursday, February 14, 2019

Name: Chip D. Signer

UW NetID: abcdef

First, a quick note. This is a **take-home** exam. We are giving you certain liberties and restrictions on how you complete it (see below). Above all, we are trusting you to comply with the stated rules and to complete the exam honestly. Failure to do so will result in a **failing grade** and **disciplinary action**.

Good luck! And remember, if you're stupid enough to cheat, I'm stupid enough to catch you.

- Max

Instructions

- **You may not collaborate.** You must complete the exam alone.
- You may ask clarifying questions on Piazza. Use the `midterm` tag and make the question **only visible to instructors**.
- Show scratch work for partial credit, but put your final answers in the blanks provided.
- Write your UW NetID on the top right corner of **every page**.
- The last page is a reference sheet. Please detach it from the rest of the exam. **Do not scan the reference sheet**.
- The exam is **open course material**. You may use content from the course website and the book, including slides, lectures, and section material.
- The exam should take just under 1 hour.
- If you can't get something, relax. Show what you know and you'll get partial credit.
- The exam totals 100 regular points and 10 extra credit points.
- **The exam is due Thursday, February 14 at 11:59pm. You must scan and submit it to Gradescope according to the instructions on Piazza.**

Question:	Number representation	Pointers	x86-64	Procedures	*Extra Credit*	Total
Points:	20	30	25	25	10	110
Score:						

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Question 1: Number representation **(20 total points)**

(a) (6 points) If we have seven (7) bits to represent integers, what is largest unsigned number and what is largest 2s complement signed number we can represent (in decimal **and** binary)?

Largest unsigned: 1111 111 (127)

Most positive signed: 0111 111 (63)

Most negative signed: 1000 000 (-64)

(b) (3 points) Complete the code below using only the space underlined (no extra lines of C). The function `is_negative` should return 1 if `x` is negative, and 0 otherwise. You **may not use the comparison operators** < and >.

```
int is_negative(int x)
{
  return !!(x & (1 << 31)) // or equivalent ;
}
```

(c) (2 points) Is floating point addition associative? (Does $a + (b + c) = (a + b) + c$?) Explain in 1 sentence.

Solution: No. Rounding can make small additions and subtractions not do anything.

(d) (2 points) Is floating point addition commutative? (Does $a + b = b + a$?) Explain in 1 sentence.

Solution: Yes. Order does not matter.

(e) (2 points) Explain in 1-2 sentences why testing for float equality (ex: `f1 - 1.0 == f2`) is rarely useful and should be done with caution.

Solution: Mathematically equal expressions might be slightly off in floating point due to rounding.

(f) (5 points) Does the following function always return? If so, explain what it returns. If not, explain why.

```
float add_loop() {
    float f1 = 1E30;    // this is 1 * 10^30 in decimal
    float f2 = 1E-30;
    while (f1 > 1E29) {
        f1 -= f2;
    }
    return f1;
}
```

Solution: It does not return. It loops forever because the f1 - f2 results in f1.

Question 2: Pointers **(30 total points)**

For this problem we are using a 64-bit x86-64 machine (**little endian**). The current state of memory (values in hex) is shown below:

Word Addr	+0	+1	+2	+3	+4	+5	+6	+7
0x00	BD	28	ED	02	35	72	3A	AF
0x08	66	6F	B1	E9	00	FF	5D	4D
0x10	86	06	04	30	64	31	8C	B3
0x18	63	78	1E	1C	25	34	EE	93
0x20	42	6C	65	67	DE	AD	BE	EF
0x28	CA	FE	D0	0D	1E	93	FA	CE

(a) (16 points) Write the value **in hexadecimal** of each expression within the commented lines at their respective state in the execution of the given program. Write UNKNOWN in the blank if the value cannot be determined.

```
int main(int argc, char** argv) {
    char *charP;
    short *shortP;
    int *intP = 0x00;
    long *longP = 0x28;

    // The value of intP is:           0x 00 00 00 00 00 00 00 00

    // *intP                           0x 02 ED 28 BD

    // &intP                           0x UNKNOWN

    // longP[-2]                       0x 93 EE 34 25 1C 1E 78 63

    charP = 0x20;
    shortP = (short *) intP;
    intP++;
    longP--;

    // *shortP                         0x 28 BD

    // *intP                           0x AF 3A 72 35

    // *((int*) longP)                 0x 67 65 6C 42

    // (short*) (((long*) charP) - 2)  0x 10
}
```

(b) Classic arcade games such as PacMan displayed ranked player scores after a game over. Below we define a struct (`Score`) to store the information.

```
struct Score {
    char name[4];
    int  rank;
    long score;
};
```

Answer the following questions using the current state of memory (from previous page):

i. (2 points) What is the size (in bytes) of our struct `Score`? 16

ii. (4 points) Given a `struct Score *p;`, write an expression equivalent to `p->rank` that uses pointer arithmetic and casting instread of struct field access notation (dot and arrow).

`*(((int*)p) + 1)`

Suppose we have some array of scores (defined below) that begins at address `0x00` in the table on the previous page.

```
Score scores[3];    // Address of scores = 0x00
```

iii. (2 points) What is the value (in hex) of `scores[1].score`? 0x 93 EE 34 25 1C 1E 78 63

iv. (2 points) Which value is greater? (Circle one)

`scores[0].name[3]`   `scores[2].name[1]`

Solution: 0x 02 is less than 0x 6c (circle the second one)

Suppose we were to switch the order in which the fields of `Score` are declared to the following:

```
struct Score {
    char name[4];
    long score;
    int  rank;
};
```

v. (2 points) What is the size (in bytes) of our new struct `Score`? 24

vi. (2 points) What is the size (in bytes) of our new array `scores`? 72

Question 3: x86-64 **(25 total points)**

Suppose we have the following assembly code for a C function called `mystery`:

```
 1  mystery:
 2      movl $0, %eax
 3  .L1:
 4      movb (%rdi), %cl
 5      cmpb %cl, (%rsi)
 6      je .L2
 7      jl .L3
 8      addb $1, (%rdi)
 9      jmp .L4
10  .L3:
11      addb $1, (%rsi)
12  .L4:
13      addb $1, %eax        // this line is buggy
14      jmp .L1
15  .L2:
16      ret
```

(a) (3 points) The assembler would reject line 13 because of a problem. Describe the problem in 1 sentence and provide a fix.

Solution: Change `addb` to `addl`. `%eax` is 4 bytes, and so needs the `l` suffix.

(b) (4 points) How does the `je` on line 6 "know" whether to jump or not? What about the `jl` on line 7? Explain in at most 1 sentence each.

Solution: They both are based on the condition codes set by the `cmpb` on line 5.

(c) (18 points) Fill in the C skeleton below so that the C definition of `mystery` has the same behavior as the (fixed) assembly version above.

```
int mystery(      char*      p1,       char*       p2) {

    int x =                       0                       ;

    while(                 *p1 != *p2                    ) {

        if(                  *p1 < *p2                   ) {

                             *p1 += 1                      ;

        } else {

                             *p2 += 1                      ;
        }

                          x += 1                         ;
    }
    return x;
}
```

Question 4: Procedures (25 total points)

Consider the following implementation of `accumulate` which recursively adds the first n numbers. The C and assembly are shown below.

In the questions below, **use the line numbers given to refer to parts of the assembly**.

```
unsigned accumulate(unsigned n, unsigned total_so_far) {
    if (n == 0)
        return total_so_far;
    return accumulate(n - 1, n + total_so_far);
}
```

```
 1  accumulate:
 2      subq    $8, %rsp
 3      movl    %esi, %eax
 4      testl   %edi, %edi
 5      je     .L1
 6      addl    %edi, %esi
 7      subl    $1, %edi
 8      call    accumulate
 9  .L1:
10      addq    $8, %rsp
11      ret
```

(a) (2 points) List the **callee**-saved registers (if any) used by `accumulate`.

Solution: None aside from `%rsp`.

(b) (4 points) The x86-64 ABI states (and the hardware itself prefers) that `%rsp` should be 16-byte aligned right before a `call` instruction. Which instructions are responsible for ensuring this? In a sentence or less, explain why these instructions are necessary to satisfy the 16-byte alignment of `call`s.

Solution: 2 (and optionally 8 and 10). It adds 8 bytes to the stack because the call adds eight.

(c) Consider the behavior of `accumulate(6, 0)`

i. (1 point) What does it return? 21

ii. (2 points) How many stack frames will it use in total? 7

iii. (2 points) What is the size of a single stack frame (in bytes)? 16 bytes

iv. (2 points) How much total stack space does this call use (in bytes)? 7 * 16 = 112 bytes

(d) (4 points) How much total stack space does `accumulate(n, 0)` use? Write your answer in terms of n.

Solution: $16 \times (n + 1)$

You wisely observe that calling and returning immediately (lines 8-11 in the assembly) seems wasteful. So you decide to replace the `call` instruction on line 8 with `jmp accumulate`. You also note that this new version **returns the same answer**. The remaining questions refer to this modification.

(e) (4 points) The modified version now violates stack discipline. After calling the modified `accumulate` procedure, a register will be different than before (and shouldn't be). What is that register? Briefly state how to fix this problem by adding, removing, or changing a small number of instructions, and **why** you can do this to this modified version of the program but not the original.

Solution: `%rsp` is changed. Remove the `add` and `sub` on lines 2 and 10. The procedure is no longer recursive, so it no longer needs to align the stack for a `call` instruction.

(f) (4 points) After the fix in part (e), how much stack total space will a call to `accumulate(n, 0)` procedure use? State your answer as a number of bytes in terms of n.

Solution: 0 bytes (or 8 bytes if you include the call)

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Question 5: *Extra Credit* *(10 total points)*

```
unsigned foobar(unsigned x) {
    x = ((x & 0x55555555) <<  1) | ((x & 0xAAAAAAAA) >>  1);
    x = ((x & 0x33333333) <<  2) | ((x & 0xCCCCCCCC) >>  2);
    x = ((x & 0x0F0F0F0F) <<  4) | ((x & 0xF0F0F0F0) >>  4);
    x = ((x & 0x00FF00FF) <<  8) | ((x & 0xFF00FF00) >>  8);
    x = ((x & 0x0000FFFF) << 16) | ((x & 0xFFFF0000) >> 16);
    return x;
}
```

What does the above function `foobar` return when given the following inputs:

(a) (2 points) `foobar(1)` = `0x80000000`

(b) (2 points) `foobar(0xFFF00F00)` = `0x00F00FFF`

(c) (6 points) Explain in 1-2 sentences what `foobar` does in general.

Solution: It reverses the bits.

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CSE 351 Reference Sheet (Midterm)

Binary	Decimal	Hex
0000	0	0
0001	1	1
0010	2	2
0011	3	3
0100	4	4
0101	5	5
0110	6	6
0111	7	7
1000	8	8
1001	9	9
1010	10	A
1011	11	B
1100	12	C
1101	13	D
1110	14	E
1111	15	F

2^0	2^1	2^2	2^3	2^4	2^5	2^6	2^7	2^8	2^9	2^{10}
1	2	4	8	16	32	64	128	256	512	1024

IEEE 754 FLOATING-POINT STANDARD

Value: ±1 x Mantissa x 2^{Exponent}

Bit fields: $(-1)^S$ x 1.M x $2^{(E-\text{bias})}$

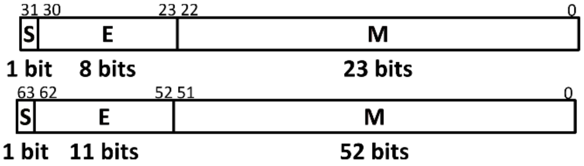
where Single Precision Bias = 127,
Double Precision Bias = 1023.

IEEE 754 Symbols

Exponent	Fraction	Object
0	0	± 0
0	≠0	± Denorm
1 to MAX - 1	anything	± Fl. Pt. Num.
MAX	0	±∞
MAX	≠0	NaN

S.P. MAX = 255, D.P. MAX = 2047

IEEE Single Precision and Double Precision Formats:



Assembly Instructions

`mov a, b`	Copy from `a` to `b`.
`movs a, b`	Copy from `a` to `b` with sign extension. Needs *two* width specifiers.
`movz a, b`	Copy from `a` to `b` with zero extension. Needs *two* width specifiers.
`leaq a, b`	Compute address and store in `b`. *Note:* the scaling parameter of memory operands can only be 1, 2, 4, or 8.
`push src`	Push `src` onto the stack and decrement stack pointer.
`pop dst`	Pop from the stack into `dst` and increment stack pointer.
`call <func>`	Push return address onto stack and jump to a procedure.
`ret`	Pop return address and jump there.
`add a, b`	Add `a` to `b` and store in `b` (and sets flags).
`sub a, b`	Subtract `a` from `b` (compute `b-a`) and store in `b` (and sets flags).
`imul a, b`	Multiply `a` and `b` and store in `b` (and sets flags).
`and a, b`	Bitwise AND of `a` and `b`, store in `b` (and sets flags).
`sar a, b`	Shift value of `b` *right* (*arithmetic*) by `a` bits, store in `b` (and sets flags).
`shr a, b`	Shift value of `b` *right* (*logical*) by `a` bits, store in `b` (and sets flags).
`shl a, b`	Shift value of `b` *left* by `a` bits, store in `b` (and sets flags).
`cmp a, b`	Compare `b` with `a` (compute `b-a` and set condition codes based on result).
`test a, b`	Bitwise AND of `a` and `b` and set condition codes based on result.
`jmp <label>`	Unconditional jump to address.
`j* <label>`	Conditional jump based on condition codes (*more on next page*).
`set* a`	Set byte based on condition codes.

Conditionals

Instruction	Condition	`(op) s, d`	`test a, b`	`cmp a, b`
`je` “Equal”	`ZF`	`d (op) s == 0`	`b & a == 0`	`b == a`
`jne` “Not equal”	`~ZF`	`d (op) s != 0`	`b & a != 0`	`b != a`
`js` “Sign” (negative)	`SF`	`d (op) s < 0`	`b & a < 0`	`b-a < 0`
`jns` (non-negative)	`~SF`	`d (op) s >= 0`	`b & a >= 0`	`b-a >= 0`
`jg` “Greater”	`~(SF^OF) & ~ZF`	`d (op) s > 0`	`b & a > 0`	`b > a`
`jge` “Greater or equal”	`~(SF^OF)`	`d (op) s >= 0`	`b & a >= 0`	`b >= a`
`jl` “Less”	`(SF^OF)`	`d (op) s < 0`	`b & a < 0`	`b < a`
`jle` “Less or equal”	`(SF^OF) | ZF`	`d (op) s <= 0`	`b & a <= 0`	`b <= a`
`ja` “Above” (unsigned >)	`~CF & ~ZF`	`d (op) s > 0U`	`b & a < 0U`	`b > a`
`jb` “Below” (unsigned <)	`CF`	`d (op) s < 0U`	`b & a > 0U`	`b < a`

Registers

Name	Convention	Name of “virtual” register		
		Lowest 4 bytes	Lowest 2 bytes	Lowest byte
`%rax`	Return value – Caller saved	`%eax`	`%ax`	`%al`
`%rbx`	Callee saved	`%ebx`	`%bx`	`%bl`
`%rcx`	Argument #4 – Caller saved	`%ecx`	`%cx`	`%cl`
`%rdx`	Argument #3 – Caller saved	`%edx`	`%dx`	`%dl`
`%rsi`	Argument #2 – Caller saved	`%esi`	`%si`	`%sil`
`%rdi`	Argument #1 – Caller saved	`%edi`	`%di`	`%dil`
`%rsp`	Stack Pointer	`%esp`	`%sp`	`%spl`
`%rbp`	Callee saved	`%ebp`	`%bp`	`%bpl`
`%r8`	Argument #5 – Caller saved	`%r8d`	`%r8w`	`%r8b`
`%r9`	Argument #6 – Caller saved	`%r9d`	`%r9w`	`%r9b`
`%r10`	Caller saved	`%r10d`	`%r10w`	`%r10b`
`%r11`	Caller saved	`%r11d`	`%r11w`	`%r11b`
`%r12`	Callee saved	`%r12d`	`%r12w`	`%r12b`
`%r13`	Callee saved	`%r13d`	`%r13w`	`%r13b`
`%r14`	Callee saved	`%r14d`	`%r14w`	`%r14b`
`%r15`	Callee saved	`%r15d`	`%r15w`	`%r15b`

Sizes

C type	x86-64 suffix	Size (bytes)
`char`	`b`	1
`short`	`w`	2
`int`	`l`	4
`long`	`q`	8