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 1: Number representation  

(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: 

Most positive signed: 

Most negative signed: 

(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 \(>\).

```c
int is_negative(int x)
{
    return ________________;
}
```

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

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

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

```c
float add_loop() {
    float f1 = 1E30; // this is 1 * 10^30 in decimal
    float f2 = 1E-30;
    while (f1 > 1E29) {
        f1 -= f2;
    }
    return f1;
}
```
Question 2: Pointers  

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:

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

(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.

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

    // The value of intP is: 0x________________________

    // *intP 0x________________________

    // &intP 0x________________________

    // longP[-2] 0x________________________

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

    // *shortP 0x________________________

    // *intP 0x________________________

    // *((int*) longP) 0x________________________

    // (short*) (((long*) charP) - 2) 0x________________________
}
```
(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.

```c
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? __________

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

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

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

iii. (2 points) What is the value (in hex) of scores[1].score? 0x_______________

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


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

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

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

vi. (2 points) What is the size (in bytes) of our new array scores? __________
Question 3: x86-64

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.

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

```c
int mystery(int p1, int p2) {
    int x = ____________________________;
    while ____________________________ {
        if ____________________________ {
            ____________________________;
        } else {
            ____________________________;
        }
    }
    return x;
}
```
Question 4: Procedures

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.**

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

```assembly
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.

(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 calls.

(c) Consider the behavior of accumulate(6, 0)
   i. (1 point) What does it return?  
      ______________
   ii. (2 points) How many stack frames will it use in total?  
       ______________
   iii. (2 points) What is the size of a single stack frame (in bytes)?  
      ______________
   iv. (2 points) How much total stack space does this call use (in bytes)?  
       ______________

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

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

```c
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) = ____________________________`

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

(c) (6 points) Explain in 1-2 sentences what `foobar` does in general.
This page intentionally left blank.
### Binary Decimal Hex

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

### IEEE 754 Floating-Point Standard

- **Value:** $\pm 1 \times \text{Mantissa} \times 2^{\text{Exponent}}$
- **Bit fields:** $(-1)^e \times 1.M \times 2^{(E-\text{bias})}$

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

### IEEE Single Precision and Double Precision Formats:

- **Single Precision:**
  - 8-bits
  - 23 bits
- **Double Precision:**
  - 11 bits
  - 52 bits

### 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).
- **shr 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

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Condition</th>
<th>(op) s, d</th>
<th>test a, b</th>
<th>cmp a, b</th>
</tr>
</thead>
<tbody>
<tr>
<td>je</td>
<td>“Equal”</td>
<td>ZF</td>
<td>d (op) s == 0</td>
<td>b &amp; a == 0</td>
</tr>
<tr>
<td>jne</td>
<td>“Not equal”</td>
<td>~ZF</td>
<td>d (op) s != 0</td>
<td>b &amp; a != 0</td>
</tr>
<tr>
<td>js</td>
<td>“Sign” (negative)</td>
<td>SF</td>
<td>d (op) s &lt; 0</td>
<td>b &amp; a &lt; 0</td>
</tr>
<tr>
<td>jns</td>
<td>(non-negative)</td>
<td>~SF</td>
<td>d (op) s &gt;= 0</td>
<td>b &amp; a &gt;= 0</td>
</tr>
<tr>
<td>jg</td>
<td>“Greater”</td>
<td>~SF^OF &amp; ~ZF</td>
<td>d (op) s &gt; 0</td>
<td>b &amp; a &gt; 0</td>
</tr>
<tr>
<td>jge</td>
<td>“Greater or equal”</td>
<td>~SF^OF</td>
<td>d (op) s &gt;= 0</td>
<td>b &amp; a &gt;= 0</td>
</tr>
<tr>
<td>jl</td>
<td>“Less”</td>
<td>(SF^OF)</td>
<td>d (op) s &lt; 0</td>
<td>b &amp; a &lt; 0</td>
</tr>
<tr>
<td>jle</td>
<td>“Less or equal”</td>
<td>SF^OF</td>
<td>d (op) s &lt;= 0</td>
<td>b &amp; a &lt;= 0</td>
</tr>
<tr>
<td>ja</td>
<td>“Above” (unsigned &gt;)</td>
<td>~CF &amp; ~ZF</td>
<td>d (op) s &gt; 0U</td>
<td>b &amp; a &gt; 0U</td>
</tr>
<tr>
<td>jb</td>
<td>“Below” (unsigned &lt;)</td>
<td>CF</td>
<td>d (op) s &lt; 0U</td>
<td>b &amp; a &lt; 0U</td>
</tr>
</tbody>
</table>

### Registers

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

### Sizes

<table>
<thead>
<tr>
<th>C type</th>
<th>x86-64 suffix</th>
<th>Size (bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>char</td>
<td>b</td>
<td>1</td>
</tr>
<tr>
<td>short</td>
<td>w</td>
<td>2</td>
</tr>
<tr>
<td>int</td>
<td>l</td>
<td>4</td>
</tr>
<tr>
<td>long</td>
<td>q</td>
<td>8</td>
</tr>
</tbody>
</table>