University of Washington – Computer Science & Engineering
Autumn 2019 Instructor: Justin Hsia 2019-12-10

CSE351 FINAL

Last Name:	**Perfect**	
First Name:	**Perry**	
Student ID Number:	1234567	
Name of person to your Left | Right	Stephanie Student	LeBron Learner
All work is my own. I had no prior knowledge of the exam contents nor will I share the contents with others in CSE351 who haven't taken it yet. Violation of these terms could result in a failing grade. (please sign)		

Do not turn the page until 12:30.

Instructions

- This exam contains 14 pages, including this cover page. Show scratch work for partial credit, but put your final answers in the boxes and blanks provided.
- The last page is a reference sheet. Please detach it from the rest of the exam.
- The exam is closed book (no laptops, tablets, wearable devices, or calculators). You are allowed two pages (US letter, double-sided) of *handwritten* notes.
- Please silence and put away all cell phones and other mobile or noise-making devices. Remove all hats, headphones, and watches.
- You have 110 minutes to complete this exam.

Advice

- Read questions carefully before starting. Skip questions that are taking a long time.
- Read *all* questions first and start where you feel the most confident.
- Relax. You are here to learn.

Question	**M1**	**M2**	**M3**	**M4**	**M5**	**F6**	**F7**	**F8**	**F9**	**F10**	**Total**
Possible Points	16	4	16	23	12	10	19	18	14	18	**150**

Question M1: Numbers [16 pts]

(A) Take the 32-bit numeral (*i.e.* bit pattern) **`0xFF800000`**. Circle the number representation below that has the *smallest magnitude* (*i.e.* closest to 0) for this numeral. [4 pt]

Floating Point [✓ Two's Complement] Unsigned Two's AND Unsigned

`float`: S = 1, E = 0b1111 1111, M = 0, so $-\infty$.
`unsigned int`: value is $2^{31} + 2^{30} + \ldots + 2^{23} = 2^{31} + x$.
`int`: value is $-2^{31} + 2^{30} + \ldots + 2^{23} = -2^{31} + x$, which is smaller in magnitude.

(B) What value will be read after we try to store $\mathbf{2^{-120} - 2^{-200}}$ in a `float`? (Circle one) [4 pt]

[✓ 2^{-120}] NaN 0 $2^{-120}-2^{-200}$

2^{-120} is a representable exponent with `E` = -120+bias = 0x07. 2^{-200} is 80 exponents smaller, so way off the end of the mantissa, so subtracting has a negligible effect that gets rounded off.

(C) Complete the following C function that returns the *signed* value of the exponent (not the `E` field) of a 32-bit floating point numeral (as an `unsigned int` argument as in Lab 1b). Ignore floating point special cases for this question. [4 pt]

```
int getExp(unsigned int fp) {
    return ((fp >> 23) & 0xFF) - 127;   // could mask before shifting
}   // return value gets implicitly cast to int
```

(D) Dubs claims that the expression **`(x != (float) x)`** will return True/1 if there was *data loss* during the cast of `int x`. Do you agree? *Briefly* explain why or why not. [4 pt]

Works? (circle one): Yes [✓ No]

Explanation: During the comparison, `x` will get implicitly cast to `float`, so this expression will *always* return False/0.

Question M2: Design Question [4 pts]

(A) Assume we decided to store/encode **object files** as *text* files instead of *binary* files. Name one advantage and one disadvantage of this design decision. [4 pt]

Advantage: Some possible answers:

- Easier to read and interpret by humans
- Can be read by a human in a text editor (*i.e.* don't need to use `objdump`)

Disadvantage: Some possible answers:

- Consumes more space/memory because each hex digit of binary data now takes up 1 (ASCII) or 2 (Unicode) bytes
- More complicated process now needed by Linker (has to convert from text to binary) to build an executable

Question M3: Pointers & Memory [16 pts]

Assume a 64-bit x86-64 machine (**little endian**). Below is the buggy `pcount_r` function disassembly from the midterm, *showing where the code is stored in memory.* Hint: read the questions before the assembly!

```
00000000004005d7 <pcount_r>:
  4005d7:   b8 00 00 00 00   movl   $0x0,%eax
  4005dc:   48 85 ff         testq  %rdi,%rdi
  4005df:   75 02            jne    4005e3 <pcount_r+0xc>
  4005e1:   f3 c3            repz retq
  4005e3:   48 d1 ef         shrq   $1, %rdi
  4005e6:   e8 ec ff ff ff   callq  4005d7 <pcount_r>
  4005eb:   83 e7 01         andl   $0x1,%edi
  4005ee:   48 01 f8         addq   %rdi,%rax
  4005f1:   c3               retq
```

(A) What are the values (in hex) stored in each register shown after the following x86 instructions are executed? Use the appropriate bit widths. [8 pt]

```
leaq (%rdi,%rsi,2), %rax
addb 2(%rdi), %sil
```

Register	**Value (hex)**
`%rdi`	`0x 0000 0000 0040 05e0`
`%rsi`	`0x 0000 0000 0000 0007`
`%rax`	`0x` **`0000 0000 0040 05ee`**
`%sil`	`0x` **`ca`**

`leaq` instruction calculates the address `0x4005e0` + `2*7` = `0x4005ee`.

`addb` instruction pulls the byte at memory address `0x4005e0`+`2` = `0x4005e2`, which is `0xc3`. adding this with the lowest byte of `%rsi` yields `0xc3 & 0x07 = 0xca`.

(B) Complete the C code below to fulfill the behaviors described in the inline comments using pointer arithmetic. Let **`short* shortP = 0x4005e2`**. [8 pt]

```
long* v1 = (long*)((_int/float_*)shortP + 4);    // set v1 = 0x4005f2
short v2 = shortP[__3__];                         // set v2 = -1
```

The difference between `v1` and `shortP` is `0x10` = 16 bytes. Since by pointer arithmetic we are moving 4 "things" away, `shortP` must be cast to a pointer to a data type of size 4 bytes.

As two bytes `(short)`, `-1 = 0xFFFF`, which is found at addresses `0x4005e8` and `0x4005e9`. `0x4005e8` is 6 bytes = 3 `shorts` ahead of `shortP`.

Question M4: Procedures & The Stack [23 pts]

A *Caesar cipher* takes a string and shifts each character by the same amount (*i.e.* **`*str += shift;`** while `*str != '\0'`). For example, `"justin"` shifted by 2 becomes `"lwuvkp"`. Below is the disassembly for an *inefficient* recursive implementation `caesar` that returns the length of the string:

```
0000000000400547 <caesar>:
  400547:    0f b6 07           movzbl (%rdi),%eax        # get *str
  40054a:    84 c0              test   %al,%al
  40054c:    75 06              jne    400554 <caesar+0xd>
  40054e:    b8 00 00 00 00     mov    $0x0,%eax          # base case
  400553:    c3                 retq                      #   returns 0
  400554:    53                 push   %rbx
  400555:    8b 5c 24 10        mov    0x10(%rsp),%ebx    # get shift
  400559:    01 d8              add    %ebx,%eax
  40055b:    88 07              mov    %al,(%rdi)
  40055d:    48 83 c7 01        add    $0x1,%rdi          # next char
  400561:    53                 push   %rbx
  400562:    e8 e0 ff ff ff     callq  400547 <caesar>
  400567:    83 c0 01           add    $0x1,%eax          # length += 1
  40056a:    5b                 pop    %rbx
  40056b:    5b                 pop    %rbx
  40056c:    c3                 retq
```

(A) Which of the following *generates* the **labels** used in the disassembly above? Circle one. [2 pt]

[✓ Compiler] Assembler Linker Loader

(B) What is the return address to `caesar` that gets stored on the stack during a recursive call? Answer in hex. [2 pt]

The address of the instruction *after* the `callq`.

0x **400567**

(C) Of the 16 instructions shown in the disassembly, how many of them access memory? [4 pt]

movzbl, mov (0x400555), retq (x2), pop (x2) **READ** from memory: _**6**_ instructions

push (x2), mov (0x40055b), callq **WRITE** to memory: _**4**_ instructions

(D) *Briefly* explain the purpose of the push at `0x400554`. [2 pt]

To save the old value of the callee-saved register `%rbx`, which we are about to change.

(E) *Briefly* explain the purpose of the push at `0x400561`. Hint: what value are we pushing and where did we get it from? Read the comments! [2 pt]

> Push `%rbx`, which currently holds the value of `shift` (the 7th argument), for the recursive call to read.

(F) Assume `main` calls `caesar` on the string **`"cse"`** with a `shift` of **1**. Fill in the stack snapshot below (in hex) as this call returns to `main`. For unknown words, write "`0x unknown`". [8 pt]

`0x7fffffffdcc8`	`<ret addr to main>`	`caesar("cse",…,1)`
`0x7fffffffdcc0`	`<original rbx>`	
`0x7fffffffdcb8`	`0x` **`1`**	
`0x7fffffffdcb0`	`0x` **`400567`**	`caesar("se",…,1)`
`0x7fffffffdca8`	`0x` **`1`**	
`0x7fffffffdca0`	`0x` **`1`**	
`0x7fffffffdc98`	`0x` **`400567`**	`caesar("e",…,1)`
`0x7fffffffdc90`	`0x` **`1`**	
`0x7fffffffdc88`	`0x` **`1`**	
`0x7fffffffdc80`	`0x` **`400567`**	`caesar("",…,1)`

4 total stack frames of `caesar` created as shown above, each moving one character forward in the initial string. In the recursive case, first we push the old value in `%rbx` onto the stack before pushing the new value of `%rbx` (the value of `shift` read from the previous stack frame). The last stack frame hits the base condition and doesn't push anything onto the stack.

(G) Name a way that we can reduce the memory usage of this function (either in amount of memory or number of memory accesses) *while maintaining correct behavior and keeping it recursive* and explain why the change helps. [3 pt]

Some acceptable responses:

- Pass `shift` in an unused argument register, which saves us from pushing it to the stack on every recursive call.
- Read `shift` into a caller-saved register instead of `%rbx`, so we don't need to push the old value of the register at the beginning of every recursive call.
- Replace the first `pop` (0x40056a) with `addq $8, %rsp`, since we don't need/use the restored value of `shift`.

Question M5: C & Assembly [12 pts]

Answer the questions below about the following x86-64 assembly function, which *uses a struct* with two fields named **`one`** and **`two`**, declared in that order:

```
mystery:
        movl    $0, %eax        # Line 1
.L2:    testq   %rdi, %rdi      # Line 2
        je      .L5             # Line 3
        cmpb    %sil, (%rdi)    # Line 4
        je      .L1             # Line 5
        addl    $1, %eax        # Line 6
        movq    8(%rdi), %rdi   # Line 7
        jmp     .L2             # Line 8
.L5:    movl    $-1, %eax       # Line 9
.L1:    rep ret                 # Line 10
```

(A) `%rdi` contains a pointer to an instance of the struct. What **variable type** is field one? [2 pt]

In Line 4, `(%rdi)` is used in a `cmp`**`b`** instruction. _____**`char`**_____

(B) Based on Line 7, give a more intuitive name for the field `two` in the struct. [1 pt]

Other variants accepted. **next** or **ptr**

(C) This function fits into the following code skeleton. Fill in the corresponding parts below, using register names as variable names (*e.g.* `al` for the value in `%al`). None should be blank. Remember that the struct fields are named `one` and `two`. [9 pt]

```
int mystery( mysteryStruct* rdi, char sil ) {
   for ( eax = 0; rdi != 0; rdi = rdi->two ) {
      if ( rdi->one == sil ) {
         return eax;
      }
      eax += 1;  // can be switched with the Update statement
   }
   return -1;
}
```

Grading notes:

- **`rdi`** also accepted for loop Condition statement.
- **`*rdi`** in place of **`rdi->one`** in if-statement received partial credit.

Question F6: Structs [10 pts]

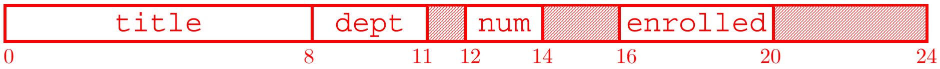
For this question, assume a 64-bit machine and the following C struct definition.

```
typedef struct {    K:
  char* title;      8  // title (e.g. "HW SW INTERFACE")
  char  dept[3];    1  // dept (e.g. "CSE")
  short num;        2  // course number (e.g. 351)
  int   enrolled;   4  // students enrolled
} course;    Kmax = 8
```

(A) How much memory, in bytes, does an instance of `course` use? How many of those bytes are *internal* fragmentation and *external* fragmentation? [6 pt]

`sizeof(course)`	Internal	External
24 bytes	**3 bytes**	**4 bytes**

Alignment requirements listed above in red next to the struct fields. A `course` instance:



The unused bytes around `num` count as internal fragmentation, the unused bytes after `enrolled` count as external fragmentation.

(B) Assume that an instance **`course`** `c` is allocated on the stack and an array **`char`** `ar[]` is allocated 40 bytes below `c` (*i.e.* `&ar + 0x28 == (`**`char*`**`)&c`). Fill in the blanks below with the new ASCII characters stored in `c.dept` after the following loop is executed. Hint: recall that the values 0x30 to 0x39 correspond to the ASCII characters `'0'` to `'9'`. [4 pt]

```
for (int i = 0; i < 52; ++i) {
   ar[i] = i;
}
```

Starting from the beginning of `ar`, we store the values 0 to 39 before we reach the struct `c`. The values 40 to 47 overwrite the bytes of `c.title` (address `0x2f2e2d2c2b2a2928`, assuming little-endian). `c.dept` then gets overwritten with the values 48 = 0x30 = `'0'`, 49 = 0x31 = `'1'`, and 50 = 0x32 = `'2'`.

`c.dept[0]`: **`'0'`**

`c.dept[1]`: **`'1'`**

`c.dept[2]`: **`'2'`**

Question F7: Caching [19 pts]

We have 256 KiB of RAM and a 4-KiB L1 data cache that is 2-way set associative with 32-byte blocks and random replacement, write-back, and write allocate policies.

(A) Calculate the TIO address breakdown: [3 pt]

Tag bits	**Index bits**	**Offset bits**
7	**6**	**5**

18 address bits. $\log_2 32 = 5$ offset bits. 2^{12}-B cache = 128 blocks. 2 blocks/set → $64 = 2^6$ sets.

(B) The code snippet below accesses two arrays of `doubles`. Assuming `i` is stored in a register and the cache starts *cold*, give the memory access pattern (read or write to which elements/addresses) and compute the **miss rate**. [6 pt]

```
#define SIZE 128
double src[SIZE];     // &src = 0x08000 (physical addr)
double dst[SIZE];     // &dst = 0x0E000 (physical addr)
for (int i = 0; i < SIZE; i += 1) {
     dst[i] = src[i];
     src[i] = i;
}
```

Per Iteration:	**Access 1:**	**Access 2:**	**Access 3:**
(circle) →	[✓ R] / W to	R / [✓ W] to	R / [✓ W] to
(fill in) →	`src[i]`	`dst[i]`	`src[i]`

`src[i]` and `dst[i]` map into the same set because their index fields match. However, our cache is 2-way set associative, so they do not conflict. Each block holds 32 B = 4 doubles, so for the 4 iterations in the same cache block, we get MMH|HHH|HHH|HHH for a miss rate of 2/12 = 1/6.

Code Miss Rate:

__**1/6**__

(C) For each of the proposed (independent) changes, draw ↑ for "increased", — for "no change", or ↓ for "decreased" to indicate the effect on the **miss rate from Part B** for the code above: [8 pt]

Use `float` instead __↓__

Double the cache size __—__

Half the associativity __↑__

No-write allocate __↑__

Using `floats` means we access each block twice as much (MR = 1/12). Doubling cache size doubles the number of sets, but `src[i]` and `dst[i]` still map to the same set. Direct-mapped would cause `src[i]` and `dst[i]` to generate conflict misses. No-write allocate means we *don't* bring in the block for `dst` into the cache on access 2, so future access 2s continue to be Misses.

(D) Assume it takes 160 ns to get a block of data from main memory. If our L1 data cache has a hit time of 5 ns and a miss rate of 5%, what is our average memory access time (AMAT)? [2 pt]

AMAT = HT + MR×MP = 5 ns + 0.05 × 160 ns = 5 + 8 ns

13 ns

SID: __1234567__

Question F8: Processes [18 pts]

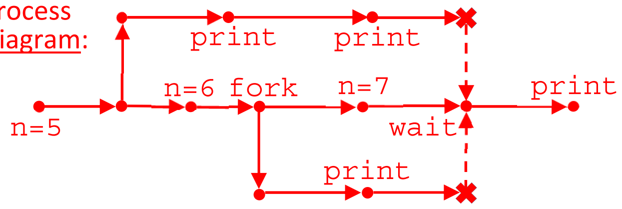
(A) The following function prints out four numbers. In the following blanks, list three possible outcomes: [6 pt]

```
void concurrent(void) {
   int n = 5;
   if (fork()) {
      n++;
      if (fork()) {
        n++;
        wait();
      }
      printf("%d, ", n);
      exit(0);
   } else {
      printf("%d, ", n);
   }
   printf("%d, ", n);
   exit(0);
}
```

The 7 possible outcomes:

```
1) 5, 5, 6, 7,
2) 5, 5, 7, 6,
3) 5, 6, 5, 7,
4) 5, 6, 7, 5,
5) 6, 5, 5, 7,
6) 6, 5, 7, 5,
7) 6, 7, 5, 5,
```

Process Diagram:



(B) For the following examples of exception causes, write "**S**" for synchronous or "**A**" for asynchronous from the perspective of the user process. [4 pt]

System call __**S**__

Divide by zero __**S**__

Segmentation fault __**S**__

Key pressed __**A**__

Everything but a key press is caused by an assembly instruction *within* your program.

(C) Fill in the following blanks with "**A**" for always, "**S**" for sometimes, and "**N**" for never if the following would be different when **context switching** to a *different* process? [4 pt]

Process ID __**A**__

Program __**S**__

PTBR __**A**__

Condition Codes __**S**__

Every process has a unique ID and its own page table, but could be running different instances of the same program. Each process has its own execution state (including the condition codes), but it is possible that the condition codes have the same *values* at the instance we switch.

(D) Is the following statement True or False? Provide a *brief* justification: a single process can execute multiple programs simultaneously. [4 pt]

Circle one: True / [✓ False]

Justification: One process is dedicated to running one program at a time. The program defines the instructions, initial memory state, etc. of the process, so two programs can't exist within the same process at once.

Question F9: Virtual Memory [14 pts]

Our system has the following setup:

- 15-bit virtual addresses and 2 KiB of RAM with 256-byte pages
- A 4-entry fully-associative TLB with LRU replacement
- A PTE contains bits for valid (V), dirty (D), read (R), write (W), and execute (X)

(A) Compute the following values: [8 pt]

page offset width **8 bits**

\# of TLB sets **1 set**

\# of virtual pages **2^7 pages**

minimum width of PTBR **11 bits**

Page offset is $\log_2 256 = 8$ bits wide. # of virtual pages is $2^{n-p} = 2^7$. The TLB is fully-associative, so only has 1 set. The page table lives in physical memory, so the PTBR must hold its physical address, which need to be at least 11 bits wide to address all 2 KiB of RAM.

(B) Assuming that the TLB is in the state shown (permission bits: 1 = allowed, 0 = disallowed), give example addresses that will fulfill the following scenarios: [6 pt]

Find the desired entry in the TLB. Because the TLB is fully-associative, the TLB tag is exactly the virtual page number (VPN). Any page offset within this page will access that TLB entry.

TLBT	PPN	Valid	D	R	W	X
0x20	0xc	1	0	1	0	0
0x7f	0xa	1	0	1	1	0
0x7e	0xf	1	0	1	1	0
0x04	0xe	1	0	1	1	1

A value in `%rip` that causes a TLB Hit and no exception: `0x0400-0x04FF`

Want TLB entry with `V=1`, `X=1` → VPN `0x04`.

A *write* address that causes a TLB Hit and segmentation fault: `0x2000-0x20FF`

Want TLB entry with `V=1`, `W=0` → VPN `0x20`.

Grading notes:

- Answers without leading zeros accepted.

Question F10: Memory Allocation [18 pts]

(A) In the following code, briefly identify the TWO memory issues and their fixes. [6 pt]

```
int N = 32;
long* func(long src[]) {
   long* p = (long*) malloc(N * sizeof(long));
   for (int i = 0; i < N; i++) {
      p[i] += src[i];
   }
}
```

Error 1:	Using uninitialized memory in `p[i]`.
Fix 1:	Replace `malloc` with `calloc` or Change `p[i] += src[i];` to `p[i] = src[i];`
Error 2:	Memory leak – no way to access malloc'ed memory once `func` returns.
Fix 2:	Add `return p;` at end of `func`.

(B) We are using a dynamic memory allocator on a **64-bit machine** with an **explicit free list**, **16-byte boundary tags**, and **8-byte alignment**. Assume that a footer is always used. [6 pt]

Request	block addr	return value	block size	internal fragmentation in this block
`p = malloc(9);`	0x628	0x_638_	__48__ bytes	__39__ bytes

Payload (returned addr) starts a header size after the block. Need at least 32 B for boundary tags and 9 B for payload = 41 B; padding for 8-B alignment gets us to **48 B** (also the minimum block size in this explicit free list). Internal fragmentation is block size – payload = 48 – 9 = **39 B**.

(C) Consider the C code shown here. Assume that the `malloc` call succeeds and that all variables are stored in memory (not registers). In the following groups of expressions, **circle the one** whose returned *value* (assume just before `return 0`) is **largest**. [6 pt]

```
#include <stdlib.h>
long glob = 10;
char* str = "351";

int main() {
    short* sp = malloc(8);
    int ONE = 1;
    free(sp);
    return 0;
}
```

Group 1:	[✓ `&sp`]	`sp`	`&str`
Group 2:	[✓ `&glob`]	`main`	`str`
Group 3:	`glob`	`ONE`	[✓ `*str`]

8) `&sp`/`&ONE`	(Stack)
7) `sp`	(Heap)
6) `&glob`/`&str`	(Static Data)
5) `str`	(Literals)
4) `main`	(Code)
3) `*str`	(`'3'` = 0x33)
2) `glob`	(10)
1) `ONE`	(1)