Exam Statistics:

Min: 27/61
Median: 53/61
Max: 61/61

Mean: 51.25/61
StdDev: 7.66/61

Low Scoring ?s:

5.2 - 53%
4.2 - 57%
4.4 - 57%
4.3 - 74%
7.2 - 75%
8.9 - 77%
5.3 - 78%

Many questions scored >95%

Q1 Instructions and Pledge

1 Point

This exam consists of 8 multi-part questions (plus the pledge), and you have 3 hours — budget your time wisely. This is a closed-book, closed-note exam, and "cheat sheets" are not allowed. During the exam you must not refer to the textbook, course materials, notes, or any information on the Internet other than the FAQ and AARCH64 reference linked below. You may not compile or run any code on armlab or any other machine. You may use blank paper as scratch space, but you must enter your answer in the online system in order to receive credit. You are not allowed to communicate with any other person, whether inside or outside the class. You may not send the exam problems to anyone, nor receive them from anyone, nor communicate any information about the problems or their topics.

If you have questions about the wording of some problem, please refer to the FAQ at the following URL:
https://docs.google.com/document/d/e/2PACX-1vQ3tv6HDlQ6HfhJE4NVvnQXDAInCTOcotrOWj_kMJtc3PMXV1ny2K0QbwCnVNw1_1eTxWLwghFALW/pub
*You may also post a **private** message on Ed, but we only guarantee that we'll be available during the following hours:*

- Friday, 12/17, 12:00 noon – 10:00 PM EST
- Saturday, 12/18, 7:00 PM – 10:00 PM EST
- Sunday, 12/19, 7:00 PM – 10:00 PM EST
- Monday, 12/20, 10:00 AM – 10:00 PM EST

This examination is administered under the Princeton University Honor Code, and by signing the pledge below you promise that you have adhered to the instructions above. ***Please type out the Honor Code pledge exactly as follows, including this exact spelling and punctuation:***

> *I pledge my honor that I have not violated the Honor Code during this examination.*

I pledge my honor that I have not violated the Honor Code during this examination.

Now type your name as a signature confirming that you have adhered to the Honor Code:

Your signature here.

Q2 C and Assembly Mix 'n Match

4 Points

For this and the following questions, please refer to the AARCH64 quick reference at the following URL (same as the FAQ):
https://docs.google.com/document/d/e/2PACX-1vQ3tv6HDlQ6HfhJE4NVvnQXDAInCTOcotrOWj_kMJtc3PMXV1ny2K0QbwCnVNw1_1eTxWLwghFALW/pub
Please note: this is the only outside reference to which you are allowed to refer during the exam. Attempting to access any other information is a violation of the honor code.

Now study the following four simple functions - two in AARCH64 assembly language and two in C:

```
a:
    cbz     w1, a_1
    udiv    w0, w0, w1
a_1:
    ret
```

```
b:
    ret
```

```
unsigned int c(unsigned int x, unsigned int y)
{
    if (y < x)
        return y;
    else
        return x;
}
```

```
unsigned int d(unsigned int x, unsigned int y)
{
    return x * y;
}
```

For each of the following unknown functions, ***select which of the functions above (a-d) has the same effect***.

Q2.1
1 Point

```
e:
    cmp     w0, w1
    bhs     e_1
    ret
```

```
e_1:
    mov     w0, w1
    ret
```

- ○ Same effect as function `a`
- ○ Same effect as function `b`
- ◉ Same effect as function `c`
- ○ Same effect as function `d`

EXPLANATION

If the first argument is >= the second argument, we skip to e_1 and therefore return the second argument. Otherwise, we return the first argument. Comparing to function c(), we see that there is a difference in logic, but only if the arguments are equal. Therefore, this code has the same effect as c().

Q2.2

1 Point

```
f:
    mov     w2, 0
    cbnz    w1, f_1
    ret
f_1:
    subs    w0, w0, w1
    blo     f_2         // Hint: branches if w0 < w1
    add     w2, w2, 1
    b       f_1
f_2:
    mov     w0, w2
    ret
```

- ◉ Same effect as function `a`
- ○ Same effect as function `b`
- ○ Same effect as function `c`
- ○ Same effect as function `d`

EXPLANATION

The code repeatedly subtracts the second argument from the first, until the first argument is smaller than the second. It returns the number of times the loop executed. We recognize this as an implementation of (unsigned) integer division, the same as function a. Note that both a and f immediately return if we attempt to divide by zero.

Q2.3

1 Point

```
g:
    mov     w2, w0
    mov     w0, wzr
    cbnz    w1, g_1
    ret
g_1:
    add     w0, w0, w2
    sub     w1, w1, 1
    cbnz    w1, g_1
    ret
```

- ○ Same effect as function `a`
- ○ Same effect as function `b`
- ○ Same effect as function `c`
- ◉ Same effect as function `d`

EXPLANATION

This is, in some ways, the opposite of f: we add the first argument to itself, with the number of iterations given by the second argument. This is a multiplication, just like function d()

Q2.4

1 Point

```
h:
    sub     sp, sp, 16
    str     x30, [sp]
    str     w0, [sp,8]
    str     w1, [sp,12]
    add     w0, w0, w1
    ldr     w1, [sp,12]
    sub     w0, w0, w1
    ldr     x30, [sp]
    add     sp, sp, 16
    ret
```

- ○ Same effect as function `a`
- ◉ Same effect as function `b`
- ○ Same effect as function `c`
- ○ Same effect as function `d`

EXPLANATION

This is a roundabout way of doing nothing. We allocate a stack frame; save x30, w0, and w1 onto it; add w1 to w0; load w1 with the saved w1; subtract w1 from w0; and clean up the stack. The net effect is that no registers were changed, and there were no side effects. We might as well have skipped everything except the ret.

Q3 GCD and LCM

9 Points

In precept, you saw both the C and assembly language code to calculate the GCD (Greatest Common Divisor) of two integers using Euclid's algorithm.

Here is a mildly-edited version of the assembly language code:

```
1       MISSING .SECTION DIRECTIVE
2   promptStr:
3       .string "Enter an integer: "
4   scanfFormatStr:
5       .string "%ld"
6   printfFormatStr:
7       .string "The gcd is %ld\n"

        //-------------------------------------------------------------
        // Return the greatest common divisor of lFirst and lSecond.
        // long gcd(long lFirst, long lSecond)
        //-------------------------------------------------------------
8       .equ    GCD_STACK_BYTECOUNT, 48
9       .equ    LABSSECOND, 8
10      .equ    LABSFIRST, 16
11      .equ    LTEMP,     24
12      .equ    LSECOND,   32
13      .equ    LFIRST,    40

14      .section .text
15      .global gcd

    gcd:
16      sub     sp, sp, GCD_STACK_BYTECOUNT
17      str     x30, [sp]
18      str     x0, [sp, LFIRST]
```

```
19      str     x1, [sp, LSECOND]
20      ldr     x0, [sp, LFIRST]
21      bl      labs
22      str     x0, [sp, LABSFIRST]
23      ldr     x0, [sp, LSECOND]
24      bl      labs
25      str     x0, [sp, LABSSECOND]

    gcdLoop:
26      ldr     x0, [sp, LABSSECOND]
27      cmp     x0, 0
28      beq     gcdLoopEnd
29      ldr     x0, [sp, LABSFIRST]
30      ldr     x1, [sp, LABSSECOND]
31      sdiv    x2, x0, x1
32      mul     x3, x2, x1
33      sub     x4, x0, x3
34      str     x4, [sp, LTEMP]
35      ldr     x0, [sp, LABSSECOND]
36      str     x0, [sp, LABSFIRST]
37      ldr     x0, [sp, LTEMP]
38      str     x0, [sp, LABSSECOND]
39      b       gcdLoop

    gcdLoopEnd:
40      ldr     x0, [sp, LABSFIRST]
41      ldr     x30, [sp]
42      add     sp, sp, GCD_STACK_BYTECOUNT
43      ret
```

Q3.1

1 Point

At line 1 of this code, there is a missing `.section` directive. What should it be? ***If multiple options are valid, select the one that best corresponds to idiomatic C code like we've modeled in precept exercises.***

- ○ `.section .bss`
- ○ `.section .data`
- ◉ `.section .rodata`
- ○ `.section .stack`
- ○ `.section .text`

EXPLANATION

This section contains strings that are passed to printf() and scanf(). While it is possible that they were allocated as (read-write) arrays, it is much more likely that they were string literals in the C code. Therefore, the most likely explanation is that this is the RODATA section.

Q3.2

1 Point

Turning to the `gcd` function itself, it appears that most of the comments are missing. ***Referring to the line numbers above, where would you insert each of the following comments?*** Note that a comment should describe the block of code that ***follows*** it, which should include all loads of variables, computation, stores of results, etc.

`// Prolog`

- ○ Before line 1
- ◉ Before line 16
- ○ Before line 17
- ○ Before line 18
- ○ Before line 20

EXPLANATION

The prolog contains all the code to set up the stack frame and save necessary registers onto it.

Q3.3

1 Point

`// lAbsFirst = labs(lFirst)`

- ○ Before line 18
- ◉ Before line 20
- ○ Before line 21
- ○ Before line 22
- ○ Before line 29

EXPLANATION

While the actual call to labs() is on line 21, line 20 loads lFirst into x0, where it will be used as the argument to labs(). Then, line 22 stores the result into lAbsFirst.

Q3.4

1 Point

```
// lTemp = lAbsFirst % lAbsSecond
```

- (•) Before line 29
- ( ) Before line 31
- ( ) Before line 34
- ( ) Before line 35
- ( ) Before line 37

EXPLANATION

Again, the actual modulo computation is on lines 31-33, but line 29 begins the process of loading the variables used in the calculation.

Q3.5

1 Point

```
// lAbsFirst = lAbsSecond
```

- ( ) Before line 29
- ( ) Before line 30
- (•) Before line 35
- ( ) Before line 36
- ( ) Before line 38

EXPLANATION

Lines 35 and 36 correspond to this code.

Q3.6

1 Point

```
// Epilog and return lAbsFirst
```

- Before line 36
- Before line 40
- Before line 41
- Before line 42
- Before line 43

EXPLANATION

The epilog consists of loading the return address and cleaning up the stack frame (lines 41-42), but line 40 loads lAbsFirst into x0 to serve as the return value.

Q3.7

1 Point

We now want to use the `gcd` code in the computation of the LCM (Least Common Multiple), using the formula
$lcm(i, j) = i * j / gcd(i, j)$.
Here is AARCH64 assembly language code to do the calculation:

```
        //-------------------------------------------------------------
        // Return the lowest common multiple of lFirst and lSecond.
        // long lcm(long lFirst, long lSecond)
        //-------------------------------------------------------------
1       .equ    LCM_STACK_BYTECOUNT, 48
2       LLCM    .req x23
3       LGCD    .req x22
4       LPROD   .req x21
5       LSECOND .req x20
6       LFIRST  .req x19

7       .section .text
8       .global lcm
    lcm:
        // Prolog
9       sub     sp, sp, LCM_STACK_BYTECOUNT
10      str     x30, [sp]
11      str     x19, [sp, 8]
12      str     x20, [sp, 16]
13      str     x21, [sp, 24]
14      str     x22, [sp, 32]
15      str     x23, [sp, 40]

        // Store parameters in registers
16      mov     LFIRST, x0
17      mov     LSECOND, x1
```

```
        // MISSING COMMENT #1
18      bl      gcd
19      mov     LGCD, x0

        // lProd = lFirst * lSecond;
20      MISSING INSTRUCTION

        // MISSING COMMENT #2
21      sdiv    LLCM, LPROD, LGCD

        // Epilog and return lAbsFirst
22      mov     x0, LLCM
23      ldr     x30, [sp]
24      ldr     x19, [sp, 8]
25      ldr     x20, [sp, 16]
26      ldr     x21, [sp, 24]
27      ldr     x22, [sp, 32]
28      ldr     x23, [sp, 40]
29      add     sp, sp, LCM_STACK_BYTECOUNT
30      ret
```

There is a missing comment (#1) before line 18. What should it read to correspond to the probable flattened C code from which the assembly language was generated?

- `gcd();`
- `gcd(lGcd);`
- `lGcd = gcd();`
- `lGcd = gcd(x0, x1);`
- `lGcd = gcd(lFirst, lSecond);`

EXPLANATION

Even though lines 16 and 17 stored lFirst and lSecond into registers x19 and x20, copies of those arguments still exist in x0 and x1, which is where gcd() expects to find them. Therefore, we can simply call gcd (line 18) and store the result in x22 (line 19) to implement the above code.

Q3.8

1 Point

There is a missing instruction on line 20. What should it read?

- (●) `mul LPROD, LFIRST, LSECOND`
- ( ) `mul LFIRST, LSECOND, LPROD`
- ( ) `mul LPROD, x0, x1`
- ( ) `mul x0, x1, LPROD`
- ( ) `mul LPROD, [sp,8], [sp,16]`
- ( ) `mul [sp,8], [sp,16], LPROD`

EXPLANATION

For the mul instruction, the destination register is the first operand, followed by the two source registers.

Q3.9

1 Point

There is a missing comment (#2) before line 21. What should it read to correspond to the probable flattened C code from which the assembly language was generated?

- ( ) // lLcm = lGcd / lProd;
- (●) // lLcm = lProd / lGcd;
- ( ) // lLcm = sdiv();
- ( ) // lGcd = lProd / lLcm;
- ( ) // lGcd = sdiv();

EXPLANATION

Again, the destination of the sdiv (signed integer division) instruction comes first, so we need to divide lProd by lGcd and store the results in lLcm.

Q4 I thought we were done with questions about strcpy...

12 Points

Recall that the C standard library's `strcpy` function copies a string to a destination from a source, and returns the address of the destination string:

```
char *strcpy(char *dest, const char *src);
```

In Assignment 2, you wrote two C implementations of `Str_copy`, which was intended to mimic `strcpy`. One implementation accessed elements of the source and destination strings by index,

changing the index to iterate through the string, while the other implementation accessed elements of the source and destination strings by pointer dereference, and moved the pointer to iterate through the string.

In this problem, you will do the same thing, except in AARCH64 assembly language. You will write both the index-iterating version, `strcpyi`, and the pointer-iterating version, `strcpyp`. To get started, you will first complete the flattened C code for the two functions. You can then compose your assembly by translating your flattened C code; however, you are not required to comment your assembly code with the flattened C statements. Also, recall that the `assert` validation in the C code does not get translated into assembly.

Your assembly functions should ***not*** use either the stack or callee-saved registers to store local variables or saved parameters, but instead do all their work using the caller-saved scratch registers. And since your functions will not call any other functions, they do not need to save x30, and thus do not need to manage a stack frame at all in a prolog or epilog.

Note: each implementation can be completed in about a dozen lines of code or less. If you are writing considerably more than that, you may be off on the wrong track.

Q4.1

2 Points

```
/* Copy string from src to dest using index iteration. Return dest. */
char *strcpyi(char *dest, const char *src) {
     assert(dest != NULL);
     assert(src != NULL);
```

```
}
```

EXPLANATION

Sample implementation:

```
    size_t ind = 0;
loop:
    dest[ind] = src[ind];
    if (src[ind] == '\0') goto endloop;
    ind++;
    goto loop;
endloop:
    return dest;
```

Many alternatives are possible. Here are three common variations:

- returning dest directly from the if statement instead of having an endloop section;
- checking for '\0' before rather than after the assignment, then doing the final '\0' assignment separately after jumping to endloop;
- doing the assignment in the conditional, using the C idioms that assignment returns the value assigned and '\0' (aka ASCII 0) evaluates as FALSE

Q4.2

4 Points

Hint: use the register+register addressing mode.

```
    // Copy string from src to dest using index iteration. Return dest.
    // char *strcpyi(char *dest, const char *src)
    .global strcpyi
strcpyi:
```

EXPLANATION

Sample implementation:

```
   DEST .req x0
   SRC  .req x1
   IND  .req x2
   C    .req w3
   mov  IND, 0
loop:
   ldrb C, [SRC,IND]
   strb C, [DEST,IND]
   cmp  C, wzr
   beq  endloop
   add  IND, IND, 1
   b    loop
endloop:
   ret  // dest still in x0
```

Many other code sequences are possible, but it's important to keep in mind that dest (which started out in x0) needs to still be in x0 when the function returns. It is possible to write this code without using the register+register addressing mode, but doing so would require additional instructions to do the addition "by hand".

Q4.3

2 Points

```
/* Copy string from src to dest using pointer iteration. Return dest. */
char *strcpyp(char *dest, const char *src) {
     assert(dest != NULL);
     assert(src != NULL);
```

```
}
```

EXPLANATION

Sample implementation:

```
    char *curr = dest;
loop:
    *curr = *src;
    if (*src == '\0') goto endloop;
    curr++;
    src++;
    goto loop;
endloop:
    return dest;
```

Q4.4

4 Points

```
    // Copy string from src to dest using pointer iteration. Return dest.
    // char *strcpyp(char *dest, const char *src)
    .global strcpyp
strcpyp:
```

EXPLANATION

Sample implementation:

```
   SRC  .req x1
   CURR .req x2
   C    .req w3
   mov  CURR, x0
loop:
   ldrb C, [SRC]
   strb C, [CURR]
   cmp  C, wzr
   beq  endloop
   add  CURR, CURR, 1
   add  SRC, SRC, 1
   b    loop
endloop:
   ret  // unmodified dest still in x0
```

Many other code sequences are possible, but it's important to keep in mind that the original dest (which started out in x0) needs to still be in x0 when the function returns. This can be done by copying x0 to another register, and then either incrementing that copy in the loop, or incrementing x0 and then restoring it after the loop.

Q5 Disassembly and Bit-Twiddling

10 Points

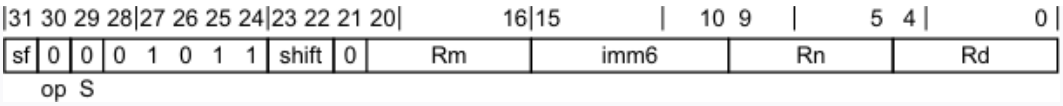
You are writing a *disassembler*: a program that takes AARCH64 machine language instructions and translates them into AARCH64 assembly language. One of the functions you need to write is

```
unsigned int getField(unsigned int uiSrc, unsigned int uiStartBit, unsigned int uiNumBits);
```

to extract each field in the instruction. Its arguments are:

`uiSrc`: a machine-language instruction, represented as a 32-bit unsigned value;
`uiStartBit`: indicates the location in `uiSrc` of the least-significant bit of the field, where `uiStartBit == 0` refers to the least-significant bit of `uiSrc`;
`uiNumBits`: the number of bits in the desired field.

For example, to get the second source register in an `ADD` instruction, which has the format below, we would call `getField(uiSrc, 16, 5)`, since the second source register `Rm` is in a 5-bit field starting at bit 16.



Q5.1

2 Points

What is the value, ***in decimal***, returned by a call to `getField(0x8B130280, 16, 5)`? ***Hint: if you're thinking about endianness, you're overthinking what is necessary to solve this problem.***

19

EXPLANATION

We want bits 16 through 20, inclusive, counting from the right. The hex digit "3" corresponds to bits 16 through 19, while bit 20 is the rightmost bit of the "1". So, we have 10011 binary, or 19 decimal.

Q5.2

1 Point

The following are some attempts to implement `getField()`, not all of which are successful. For each one, determine whether it works correctly for all valid inputs, or whether it is buggy. You should consider only valid calls to `getField()` — i.e., you should assume that `uiStartBit + uiNumBits <= 32`. ***Hint: the right-shift operator `>>`, when applied to an `unsigned int`, performs a logical right shift that fills in on the left with "0" bits.***

```
unsigned int getField1(unsigned int uiSrc, unsigned int uiStartBit, unsigned int uiNumBits)
{
    uiSrc << (32 - (uiStartBit + uiNumBits));
    uiSrc >> (32 - (uiStartBit + uiNumBits));
    uiSrc >> uiStartBit;
    return uiSrc;
}
```

○ Correct

◉ Buggy

EXPLANATION

We keep shifting uiSrc, but never store the shifted result anywhere.

Q5.3
1 Point

```
unsigned int getField2(unsigned int uiSrc, unsigned int uiStartBit, unsigned int uiNumBits)
{
    uiSrc = uiSrc << (32 - (uiStartBit + uiNumBits));
    uiSrc = uiSrc >> (32 - uiNumBits);
    return uiSrc;
}
```

◉ Correct

○ Buggy

EXPLANATION

This first shifts uiSrc far enough that the bits we don't want "fall off the end" on the left, then shifts it right exactly the right amount to leave the field we want at the right of the word.

Q5.4
1 Point

```
unsigned int getField3(unsigned int uiSrc, unsigned int uiStartBit, unsigned int uiNumBits)
{
    unsigned int result;
    result = (unsigned int) pow(2, uiNumBits) - 1;
    result &= (uiSrc >> uiStartBit);
    return result;
}
```

◉ Correct

○ Buggy

EXPLANATION

We first set result to consist of uiNumbits ones, with the remaining bits zeros. We then shift uiSrc, and zero out the unwanted bits with a bitwise and.

Q5.5
1 Point

```
unsigned int getField4(unsigned int uiSrc, unsigned int uiStartBit, unsigned int uiNumBits)
{
    unsigned int result = 0;
```

```
    unsigned int i;

    for (i = 0; i < uiNumBits; i++)
        result = (result << 1) + 1;
    result = result && (uiSrc >> uiStartBit);
    return result;
}
```

○ Correct

◉ Buggy

EXPLANATION

This approach would work, but the code carelessly uses a logical and instead of a bitwise and.

Q5.6

1 Point

```
unsigned int getField5(unsigned int uiSrc, unsigned int uiStartBit, unsigned int uiNumBits)
{
   unsigned int result = 0;
   result = ~result;
   result = result << (32 - (uiStartBit + uiNumBits));
   result = result >> (32 - (uiStartBit + uiNumBits));
   result = result & uiSrc;
   result = result >> uiStartBit;
   return result;
}
```

◉ Correct

○ Buggy

EXPLANATION

The first line sets result to a word of "1" bits. The next three lines zero out the part of uiSrc that lies to the left of the bits we want to extract. And then the final shift moves those bits to the right of uiSrc.

Q5.7

3 Points

Finally, consider disassembling the `ADR` instruction, which has the format below:

Here is part of the implementation, which relies on a working implementation of `getField()`:

```
void disassem_ADR(unsigned int uiSrc)
{
    unsigned int Rd;
    int offset;

    assert(getField(uiSrc, 31, 1) == 0);
    assert(getField(uiSrc, 24, 5) == 0x10);
    Rd = getField(uiSrc, 0, 5);
    offset = /* INSERT EXPRESSION HERE */;

    /* Now sign-extend offset, and print out the instruction. */
    /* ... */
}
```

Recall that the high-order bits of the `offset` are in the *immhi* field, while its low-order bits are in the *immlo* field. With this in mind, fill in the code marked `/* INSERT EXPRESSION HERE */`. That is, write a single expression for the offset (***before*** it is sign-extended, and ***without*** printing anything), which should involve multiple calls to `getField()` as well as any other necessary arithmetic manipulation:

```
(getField(uiSrc, 5, 19) << 2) |
getField(uiSrc, 29, 2)
```

EXPLANATION

immhi consists of bits 5 through 23 (i.e., 19 bits), while immlo consists of bits 29 through 30 (i.e., 2 bits). The two calls to getField extract those bits, and then the left-shift and bitwise or assemble them into a 21-bit value. Of course, multiplication by 4 can take the place of the left shift, and addition can be used instead of bitwise or.

Q6 Linked-List De-Linking

8 Points

Consider the following linked-list type, as well as code intended to remove all nodes containing `val` from the list:

```
struct Node {
    struct Node *next;
    int val;
```

```
};
struct List {
    struct Node *first;
};
typedef struct List *List_T;

struct Node *remove_node(struct Node *node, int val)
{
    if (!node) {
        return NULL;
    } else if (node->val == val) {
        struct Node *next = remove_node(node->next, val); /* LINE 0 */
        free(/* EXPRESSION 1 */);
        return /* EXPRESSION 2 */;
    } else {
        node->next = remove_node(node->next, val);
        return /* EXPRESSION 3 */;
    }
}

void List_remove(List_T list, int val)
{
    list->first = remove_node(list->first, val);
}
```

Fill in the missing expressions in the code above. ***Hint: draw a diagram and trace through the execution of one or two simple examples.***

Q6.1

2 Points

What should `EXPRESSION 1` be?

- (●) `node`
- ( ) `next`
- ( ) `node->next`
- ( ) `node->val`
- ( ) `NULL`

EXPLANATION

The operation of this code is slightly tricky, in that remove_node actually returns a pointer to a Node, and that pointer is assigned (either to list->first or node->next). It is recommended that you trace through how this works, using some simple examples. Turning to EXPRESSION 1, "node" points to the relevant struct Node whose val field is equal to the value we want to remove, so we want to free(node);

Q6.2
2 Points

What should `EXPRESSION 2` be?

- ○ `node`
- ◉ `next`
- ○ `node->next`
- ○ `node->val`
- ○ `NULL`

EXPLANATION

We can't return node->next, since node was already freed. On the other hand, we saved the value from the recursive call to remove_node() in the "next" variable, and that's what we want to pass up the call chain, so that the parent of this node can re-link to it.

Q6.3
2 Points

What should `EXPRESSION 3` be?

- ◉ `node`
- ○ `next`
- ○ `node->next`
- ○ `node->val`
- ○ `NULL`

EXPLANATION

In this case, we are not freeing "node", so we just return it up the call chain.

Q6.4
2 Points

We now wish to change the code so that only the ***first*** node containing `val` is removed from the list. How should `LINE 0` be changed (if the remaining code is left unchanged)?

- `struct Node *next = remove_node(node->next, NULL);`
- `struct Node *next = remove_node(NULL, val);`
- `struct Node *next = node;`
- (selected) `struct Node *next = node->next;`
- `return node;`

EXPLANATION

In this case, we want to terminate the recursion as soon as we reach a node that we want to remove. The remainder of the list (beginning with node->next) is what we should return from remove_node, so that it can be assigned to the ->next field of the parent.

Q7 How smart is the compiler?

5 Points

In lecture, we considered some cases in which a smart optimizing compiler could or could not perform an optimization. Let us consider the function `g` below, and a candidate optimization:

Original function, before optimization:

```
int g(int *x)
{
    return f(x) + f(x);
}
```

After optimization:

```
int g(int *x)
{
    return f(x) << 1;
}
```

Whether or not this optimization is valid depends, in turn, on the function `f`. In each of the following cases, could a smart optimizing compiler perform the optimization above?

Q7.1

1 Point

The following function `f` is defined in the same file as function `g`:

```
int f(int *x)
```

```
{
    printf("%d\n", *x);
    return *x + 1;
}
```

○ The above optimization to `g` ***is*** allowed

◉ The above optimization to `g` ***is not*** allowed

EXPLANATION

f() has a user-visible side effect: it writes a value to stdout. In this case, the original g() will call printf twice, while the optimized version will call it only once. So, the optimization is not allowed.

Q7.2

1 Point

The following function `f` is defined in the same file as function `g`:

```
int f(int *x)
{
   *x = *x + 1;
   return *x;
}
```

○ The above optimization to `g` ***is*** allowed

◉ The above optimization to `g` ***is not*** allowed

EXPLANATION

In this case, f()'s side effect is a bit more subtle: it modifies the value pointed to by its parameter. So the proposed optimization to g() would leave *x incremented by 1 rather than by 2, and would return 2x+2 rather than 2x+3 (if x is the original value of *x).

Q7.3

1 Point

The following function `f` is defined in the same file as function `g`:

```
int f(int *x)
{
    return *x + 1;
}
```

- (●) The above optimization to `g` ***is*** allowed
- ( ) The above optimization to `g` ***is not*** allowed

EXPLANATION

In this case, f() has no side effects, and a good optimizing compiler will be able to deduce that. So, the proposed optimization can be performed, since both the original and optimized g() will always return the same value.

Q7.4

1 Point

The following function `f` is defined in the same file as function `g`:

```
static int counter = 0;
int f(int *x)
{
    counter++;
    return *x + 1;
}
```

- ( ) The above optimization to `g` ***is*** allowed
- (●) The above optimization to `g` ***is not*** allowed

EXPLANATION

In this case, the original and optimized g() will always return the same value, but their side effects will be different. The original will increment counter twice, while the optimized version will only increment it once. Therefore, the behavior of the program as a whole would be changed by the optimization, and so it is not allowed.

Q7.5

1 Point

The function `f` is ***not*** defined in the same file as function `g`.
Its definition is known only at link time.

○ The above optimization to `g` ***is*** allowed

◉ The above optimization to `g` ***is not*** allowed

EXPLANATION

In this case, the compiler cannot tell whether f() has side effects, and it must make the conservative assumption that it might. So, it will not perform the optimization.

Q8 (Re-)Make Me!

9 Points

Here are fragments of modules that will be built into one executable named `testtable`. All pertinent information is shown.

```
/* testtable.c */
#include <stdio.h>
#include "table.h"
... rest of testtable.c

/* table.h */
#ifndef TABLE_INCLUDED
#define TABLE_INCLUDED
#include <stddef.h>
#include "mydefs.h"
... rest of table.h
#endif

/* table.c */
#include "table.h"
#include "node.h"
... rest of table.c

/* node.h */
#ifndef NODE_INCLUDED
#define NODE_INCLUDED
#include "mydefs.h"
... rest of node.h
#endif

/* node.c */
#include "node.h"
... rest of node.c

/* mydefs.h */
#ifndef MYDEFS_INCLUDED
#define MYDEFS_INCLUDED
... rest of mydefs.h
#endif
```

You have written a `Makefile` for this project that follows COS 217 best practices. Its structure is as follows:

```
TARGET1: DEPENDENCIES1
        gcc217 testtable.o table.o node.o -o testtable
TARGET2: DEPENDENCIES2
        gcc217 -c testtable.c
TARGET3: DEPENDENCIES3
        gcc217 -c table.c
TARGET4: DEPENDENCIES4
        gcc217 -c node.c
```

Answer the following questions about the `Makefile` and the behavior of `make`:

Q8.1
1 Point

The line `TARGET1: DEPENDENCIES1` should be
`testtable: testtable.o table.o node.o table.h node.h mydefs.h`

- ○ True
- ◉ False

EXPLANATION
An executable should depend only on .o files.

Q8.2
1 Point

The dependency rule for `testtable.o` should be `testtable.o: testtable.c table.h mydefs.h`

- ◉ True
- ○ False

EXPLANATION
A .o file should depend on its corresponding .c file, and any user (non-system) .h files included by it, directly or indirectly.

Q8.3
1 Point

The dependency rule for `table.o` should be
`table.o: table.c table.h stddef.h mydefs.h node.h mydefs.h`

- ○ True
- ◉ False

EXPLANATION
stddef.h should not be included, and mydefs.h should not be listed twice.

Q8.4
1 Point

The dependency rule for `node.o` should be `node.o: node.c node.h mydefs.h`

- [x] True
- [ ] False

EXPLANATION

A .o file should depend on its corresponding .c file, and any user (non-system) .h files included by it, directly or indirectly.

Q8.5

1 Point

The command `gcc217 -c testtable.c` builds `testtable`.

- [ ] True
- [x] False

EXPLANATION

Because of the -c flag, this builds testtable.o

Q8.6

1 Point

When `mydefs.h` is out of date, `table.o` gets built twice, because `table.c` depends on `mydefs.h` through both `table.h` and `node.h`.

- [ ] True
- [x] False

EXPLANATION

make executes each rule a maximum of once.

Q8.7

1 Point

After issuing the `make` command to build the program, we modify the definition of one function in `node.c`. If we issue the `make` command now, how many of the four targets in the `Makefile` will be rebuilt?

- ○ 0
- ○ 1
- ◉ 2
- ○ 3
- ○ 4

EXPLANATION

Editing node.c causes node.o to be considered out of date, causing make to rebuild node.o. That, in turn, causes testtable to be out of date, so it also gets rebuilt.

Q8.8

1 Point

After issuing the `make` command to build the program, we execute the `touch mydefs.h` command to update the timestamp for `mydefs.h` to the current time, without changing its contents. If we issue the `make` command now, how many of the four targets in the `Makefile` will be rebuilt?

- ○ 0
- ○ 1
- ○ 2
- ○ 3
- ◉ 4

EXPLANATION

testtable.c, table.c, and node.c all depend indirectly on mydefs.h. So, testtable.o, table.o, and node.o will get rebuilt. Finally, testtable will be rebuilt.

Q8.9

1 Point

If we were to rearrange the `Makefile` by swapping lines 1 and 2 (TARGET1 and its command) with lines 3 and 4 (TARGET2 and its command), then `make` would behave the same way in all situations as it does with the original `Makefile`.

- ○ True
- ◉ False

EXPLANATION

The first target is the default - it's what gets built if you just run "make" with no arguments. So, swapping lines 1 and 2 with lines 3 and 4 would change the default, building testtable.o instead of testtable when you just execute "make".

Q9 Beat the Grader!

3 Points

The following function returns a grade. You will receive 0 points if it returns an `'F'`, 1 point if it returns a `'C'`, 2 points if it returns a `'B'`, and 3 points if it returns an `'A'`. ***Note: no buffer overrun is necessary on this problem. Please do not attempt to execute one.***

```
char grader(unsigned char secret)
{
    const int princeton = -1746;
    const int beat_harvard = 18-16;
    const int beat_yale = 35-20;
    int i;

    if ((unsigned int) princeton < secret)
        return 'F';

    for (i = 0; i < 3; i++) {
        if (secret < beat_harvard || secret < beat_yale)
            return 'C';
        secret -= beat_harvard;
        secret += beat_yale;
    }

    if (secret)
        return 'B';
    else
        return 'A';
}
```

What value would you like to pass as the `secret`?

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EXPLANATION

The first if statement casts a small negative value to an unsigned int, resulting in a very large value (over 4 billion). It is thus impossible for the function to return 'F', since the range of secret is limited to 0..255. The tricky key to this problem is to realize that for secret to end up equal to zero (and thus return 'A'), we must get unsigned overflow the last time through the loop, and it must overflow by exactly 1 and no more. This precise overflow will occur if secret is incremented 1 beyond the maximum value of an unsigned char, which is 255.