Instructions:

- Print your name in the space provided below.
- This examination is closed book and closed notes, aside from the permitted one-page formula sheet. This examination is closed book and closed notes, aside from the permitted one-page fact sheet. Your fact sheet may contain definitions and examples, but it may not contain questions and/or answers taken from old tests or homework. You may include examples from the course notes.
- No calculators or other electronic devices may be used. The use of any such device will be interpreted as an indication that you are finished with the test and your test form will be collected immediately.
- Answer each question in the space provided. If you need to continue an answer onto the back of a page, clearly indicate that and label the continuation with the question number.
- If you want partial credit, justify your answers, even when justification is not explicitly required.
- There are 7 questions, some with multiple parts, priced as marked. The maximum score is 100.
- When you have completed the test, sign the pledge at the bottom of this page and turn in the test.
- If you brought a fact sheet to the test, write your name on it and turn it in with the test.
- Note that either failing to return this test, or discussing its content with a student who has not taken it is a violation of the Honor Code.

Do not start the test until instructed to do so!

Name Solution

printed

Pledge: On my honor, I have neither given nor received unauthorized aid on this examination.

signed


OKAY, HUMAN.
HUH?
BEFORE YOU HIT 'COMPILE', LISTEN UP.
YOU KNOW WHEN YOU'RE FALLING ASLEEP, AND YOU IMAGINE YOURSELF WALKING OR SOMETHING.
AND SUDDENLY YOU MISSTEP, STUMBLE, AND JOLT AWAKE?
YEAH!
WELL, THAT'S WHAT A SEGFAULT FEELS LIKE.
DOUBLE-CHECK YOUR DAMN POINTERS, OKAY?

xkcd.com

1. These questions relate to pointers, data representation, and data types in C.

a) **[4 points]** The following C code fragment is intended to sum the values in an array, from high to low. There are no syntax errors. The array `A[]` has dimension `Sz`, and `Sz` actually equals 100. However, the loop does not perform as the programmer intended. Explain exactly what happens at runtime that prevents the loop from executing as intended.

```
int32_t Sum = 0;
int32_t* elem = &A[0];
int32_t* stop = &A[Sz];
while ( elem <= stop ) {
   Sum += *elem;
   elem++;
}
```

The variable `stop` is set to the address of the next memory location after the end of the array; since the loop test uses <=, the loop will access one value beyond the end.

b) **[4 points]** Complete the following C code, so that the condition in the comment is satisfied, no matter what value `A` has, and using only the following operations: `&  |  ^  ~  +  !  *`

```
int32_t A = ???;
int32_t Y = A + (____~A + 1_____________________________);  // Y is set to 0
```

Since A is a signed integer, we need to add the negation of A; since signed values are stored using 2's complement form, -A can be computed by flipping all the bits of A and then adding 1.

c) **[4 points]** Complete the following C code, so that the condition in the comment is satisfied, no matter what value `B` has, and using only the following operations: `&  |  ^  ~  +  !  *`

```
uint32_t B = ???;
uint32_t Z = B + (_____~B + 1_____________________________);  // Z is set to 0
```

Since B is an unsigned integer, it's stored in pure base-2 form. Consider an example; suppose B is 10:

0000 0000 0000 0000 0000 0000 0000 1010

To get a result of 0, we would need to add:

1111 1111 1111 1111 1111 1111 1111 0110

which happens to be, precisely, the complement of B plus 1...

This was tricky. A common answer was ~B; but x + ~x (x being a bit) always yields 1. However, if you noticed that, you might have realized that adding 1 to that will yield 0.

2. [15 points] Consider the following three C data types:

```
struct _RGB {
   uint8_t red;
   uint8_t green;
   uint8_t blue;
};
typedef struct _RGB RGB;
```

```
struct _Pixel {
   int32_t x;
   int32_t y;
   RGB     color;
};
typedef struct _Pixel Pixel;
```

```
struct _Matches {
   uint32_t* indices;
   uint32_t  nMatches;
};
typedef struct _Matches
Matches;
```

Implement the following C function, conforming to the header comment. **Be careful of syntax in your answer!**

```
/**  Builds a list of indices of Pixels that match a given attribute.
 *
 *   Pre:     Pixels is an array of nPixels Pixel objects
 *   Returns: a pointer to a new Matches object, pointing to an array
 *              of nMatches indices corresponding to Pixel objects
 *              in Pixels[] that matches the given value of Red.
 */
Matches* findRed(uint8_t Red, const Pixel[] Pixels, uint32_t nPixels) {

    Matches* pM = malloc(sizeof(Matches));          // create Matches object

    pM->indices = malloc(nPixels * sizeof(uint32_t)); // create its array

    pM->nMatches = 0;                               // set counter for matches

    for (uint32_t pos = 0; pos < nPixels; pos++) {    // iterate through the Pixel objects

            if ( Pixels[pos].color.red == Red ) {      // see if current element is a match

                    pM->indices[pM->nMatches] = pos;      // if so, store its index, and
                    pM->nMatches++;                       // increment the counter
            }
    }
    pM->indices = realloc(pM->indices, nMatches * sizeof(uint32_t));
    return pM;                                      // return pointer to Matches object
}
```

The Matches object must be allocated dynamically so that it will continue to exist after the function returns. And the array indices the Matches object will point to must also be allocated dynamically, since there's no other valid way to create it.

Some observations:

- Simply making a declaration (Matches* M) does not create an object.
- Making a local automatic object (Matches M) does not allow you to return a pointer to a Matches object, unless you return &M, which is a pointer to a local automatic variable, which will cease to exist when the function returns.
- Incrementing the indices member of a Matches object (e.g. M->indices++) will remove your access to the beginning of the array.
- Repeatedly reallocating the array to get the exact size is wildly inefficient; the approach I used above is the correct way. However, this was not a requirement for this question.

3. Suppose we have a memory region containing the following bytes:

```
           0  1  2  3  4  5  6  7   8  9  A  B  C  D  E  F
          -------------------------------------------------
00000000  A4 2D 6A C3 60 A3 12 81  C2 BD 10 94 5D E5 04 08
00000010  88 F1 1E 3D AE 3B 8E 19  28 84 12 07 0A D1 04 53
00000020  A4 54 EE AB B5 14 7B C6  E5 87 8F C0 5B DB CA 03
00000030  10 6A A0 D7 A7 8E 63 12  39 00 85 B8 F8 06 BD EC
```

a) **[6 points]** Assume you have a pointer `p`, of type `uint8_t*`, and that `p` has been initialized to the address of the first byte in the region shown above. Complete the following C statement so that it will copy 8 bytes of data, starting with the byte pointed to by `p`, into the given variable:

```
int64_t n = ___* (int64_t*) p_____________________________________;
```

We must cast p to create a pointer whose target type contains 8 bytes, then dereference. One error was to cast to uint64_t*; this is unwise since the values are specified as signed integers.

b) **[5 points]** What value (expressed in hex) will be assigned to the given variable by the following C statement?

```
uint8_t a = *(p + 12);
```

5D

p + 12 points to the byte 12 spots after the target of p; just count it out.

c) **[4 points]** Write the values of the bytes (in the memory region shown above) that would be replaced if the following C statement was executed:

```
*(uint32_t*)(p + 16) = 0x1234;
```

88 F1 1E 3D

Due to the typecast, we will overwrite 4 bytes of memory, starting at the address p + 16. The constant shown will be "widened" with 0's for the assignment.

---

4. Suppose we have the following C code:

```
int32_t A[8] = {0, 1, 2, 3, 4, 5, 6, 7};
int32_t* p = &A[0];
```

Which element of the array `A` will be the target of each of the following pointer expressions? E.g., `A[3]`. If the pointer expression does not correspond to the address of an array element, say that instead.

a) **[3 points]** `p + 4` **A[4]**

Pointer arithmetic; this advances by 4 * sizeof(int32_t).

b) **[3 points]** `p + 8` This is one element past the end of the array.

Pointer arithmetic; this advances by 8 * sizeof(int32_t).

c) **[3 points]** `(int8_t*)p + 12` **A[3]**

Pointer arithmetic; this advances by 12 * sizeof(int8_t), or 12 bytes, which is the size of exactly 3 4-byte integers.

5. The short C program shown below compiles to the assembly code shown below:

```
int main() {

   uint32_t N = 0xFFFF0000;    // 1
   N = N >> 4;                 // 2

   int32_t M = 0xFAFAFAFA;     // 3
   M = M >> 4;                 // 4

   return 0;                   // 5
}
```

```
main:
   pushq   %rbp
   movq    %rsp, %rbp
   subq    $16,  %rsp
   movl    $-65536,  -4(%rbp)
   shrl    $4,   -4(%rbp)
   movl    $-84215046,  -8(%rbp)
   sarl    $4,   -8(%rbp)
   movl    $0,   %eax
   leave
   ret
```

a) **[6 points]** The shift instruction in line 2 of the C code is translated using a `shrl` assembly instruction, but the shift instruction in line 4 of the C code is translated using a `sarl` assembly instruction. Why does it make sense that the shift instruction in line 2 would be translated this way? Be specific.

Statement 2 is right-shifting an unsigned integer, so we need to shift in 0's for the 4 high bits; a logical right shift will do that (an arithmetic right shift would shift in copies of the former high bit, which is 1 in this case).

The biggest issue with this question was the lack of thorough explanations. It is not enough to say "We just use shrl for unsigned and sarl for signed values." You needed to explain why shrl is the appropriate instruction for an unsigned value.

b) **[10 points]** Complete the diagram of the stack frame for the function given above. Write the address for each stack element (relative to `%rbp`), and the value stored at each location (when the function completes line 4), if that value is known. Show values in hex; shade any "extra" rows in the table that are not needed for the stack frame.

The 0xFAFAFAFA value is signed, which means that the sign bit (1) is preserved during the shift. Shifting right 4 positions adds 4 new 1s to the most significant bits, or 0xF. The result of the shift is 0xFFAFAFAF.

The 0xFFFF0000 value is unsigned, which means that the sign bit is not preserved; shifting right 4 positions adds 4 new 0s to the most significant bits. The result of the shift is 0x0FFFF000.

The stack frame is allocated 16 bytes by the subq instruction in the x86 code. That means that only 4 blocks of the table to the right are needed. The bottom 2 are unnecessary and should be shaded.

The biggest issues with this question were

- **Shifting by 4 nybbles instead of by 4 bits**
- **Issues with the sarl/shrl shift behavior**
- **Not shifting at all**

rbp	old value of rbp
rbp - 4	0FFFF000
rbp - 8	FFAFAFAF
rbp - 12	
rbp - 16	

6. **[14 points]** Implement the following C function, obeying all restrictions. Violations of the restrictions will earn a score of zero.

```
/** Returns 1 if every even-indexed bit is 0, and 0 otherwise.
 *
 *  Allowed operations:  ! ~ & | ^ << >>
 *  No more than 20 uses of operators.
 *  No use of loops, if, if-else, switches.
 *  No declarations of constants wider than one byte.
 *
 *  Examples:
 *    0000 0000 0000 0000 0000 0000 0000 0000 :  1
 *    0000 0000 0000 0000 0000 0000 1000 0010 :  1
 *    0000 0000 0000 0000 0000 0000 0000 0110 :  0
 *    0100 0010 1000 0000 0000 0000 0000 0000 :  0
 */
int evensAreZero(int N) {

  int mask = 0x55;   // 0101 0101

  return (  !( (N & mask) |              // 0 unless an even-indexed bit in low nybble is 1

            (N & (mask << 8)) |          // 0 unless an even-indexed bit in 2nd nybble is 1

            (N & (mask << 16)) |         // 0 unless an even-indexed bit in 3rd nybble is 1

            (N & (mask << 24)) ) );      // 0 unless an even-indexed bit in 4th nybble is 1
}
```

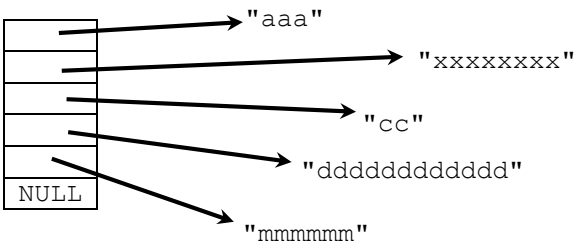
The biggest issues with this question were

- Violating the restrictions, particularly with the use of disallowed operations (+, ==) and with the use of 32-bit constants (0x55555555).
- Some students provided solutions that were effectively correct, but returned values such as 2 or 10 instead of 1. This issue was resolvable with the use of the opposite mask (using 0x55 instead of 0xAA) and applying the ! operation at the very last step.
- If you shift a 32-bit value by 32 bits, you have removed all data from that memory segment.

7. For this question, you are going to complete a short C program:

```
struct _Segment {
   int  length;
   char token;
};
typedef struct _Segment Segment;

char** builder(const Segment* const segments, int nSegments);
void writestuff(char** stuff);

int main() {

   Segment segs[5] = {{3, 'a'}, {8, 'x'}, {2, 'c'}, {12, 'd'}, {6, 'm'}};

   char** result = builder( segs, 5 );

   writestuff( result );

   delete( result );

   return 0;
}
```

The function `builder()` is intended to create an array of C-strings from an array of Segment objects. In the code shown above, `builder()` should return a pointer to an array-based structure like this:



Each array cell holds a pointer to a C-string, as described by one of the `Segment` objects; the last array cell stores `NULL`. The C-strings are stored in arrays that are exactly the right size for the specified contents, and the array of pointers is also exactly the right size.

a) [7 points] Implement the following function:

```
/**  Deallocates an array of strings, as described in the problem statement.
 *   Pre:  p points to a dynamically-allocated array of char*, each
 *         of which points to a C-string as described
 *   Post: all dynamically-allocated memory has been deallocated
 */
void delete(char** p) {

   char** current = p;              // get handle on 0th array cell
   while ( *current != NULL ) {     // walk until find NULL at end of array
      free( *current );             // deallocate the current string
      current++;                    // step to the next array cell
   }
   free( p );                       // free the array of char*
}
```

Two major issues with this question. (1) Must deallocate ALL memory – the individual strings and the char* array. (2) Pointers – difference between p, *p, and **p.

b) **[12 points]** Implement the following function. You must use pointer arithmetic, not array bracket notation when making any accesses to array elements. Violating that restriction will result in a deduction of 6 points.

```
/**  Creates an array of C-strings, as described in the problem.
 *   Pre:   segments points to an array of nSegments Segment objects
 *   Post:  an array structure, as described, has been created
 *   Returns:  a pointer to that array structure
 */
char** builder(const Segment* const segments, int nSegments) {

  char** strings = calloc(nSegments + 1, sizeof(char*));

  for (int pos = 0; pos < nSegments; pos++) {

     char* current = calloc(segments[pos].length + 1, sizeof(char));

     for (int idx = 0; idx < segments[pos].length; idx++) {

        current[idx] = segments[pos].token;
     }

     strings[pos] = current;
  }

  return strings;
}
```

The biggest issues with this question were

- Just like you had to deallocate memory for both the individual strings and the char* pointer array in Q7a, you also have to allocate memory for both: space for the char* pointer array outside the loop, and space for each individual string inside the loop.
- sizeof() exists to allow you to allocate precisely the amount of memory you need for a certain datatype. If you're creating an array of char*s, you should be using sizeof(char*). If you're creating an array of chars, you should be using sizeof(char).