The first two questions refer to the following declarations and function:

typedef struct {
  int a[3];
  short b, c;
} stuff;

stuff s[32][32];

int sum(int mode, stuff s[32][32]) {
  int i, j, a = 0;

  for (i = 0; i < 32; i++)
    for (j = 0; j < 32; j++) {
      a += s[i][j].a[mode];
      if (mode)
        a += s[i][j].c;
      else
        a += s[i][j].b;
    }

  return a;
}
For each question below, assume a 4kB direct-mapped cache that uses 8-byte blocks, the cache is initially empty, and local variables are in registers. Also assume that the array $s$ is at the address 0xA0000 in memory.

1. For each of first six memory accesses via $s$ in $\text{sum}(0, s)$, what is the accessed element, what is the accessed address, and is the access a cache hit or miss?

<table>
<thead>
<tr>
<th>Access expression</th>
<th>Access address</th>
<th>Hit or miss</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

2. What is the expected cache-miss rate of $\text{sum}(2, s)$?

3. For each of first six memory accesses via $s$ in $\text{sum}(2, s)$, what is the accessed element, what is the accessed address, and is the access a cache hit or miss?

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</tbody>
</table>

4. What is the expected cache-miss rate of $\text{sum}(0, s)$?
5. Cross out the files above that turn out to be irrelevant to the result of make && ./a.out (in the sense that erasing the file content would not change the output).

6. What does make && ./a.out print? In case you don’t compute the output correctly, to improve opportunities for partial credit, list specific functions that are called and the value that each call returns.
7. The output further below is the partial result of using `readelf` on the shared library produced by `gcc -shared` on a source file. Cross out the files among the four shown below that could not have been the source file that lead to this output.

```
1.c
extern int a;
int w();

int q()
{
  return a + w();
}

2.c
extern int a;
int q();

int w()
{
  return a + q();
}

3.c
extern int q;
int a();

int w()
{
  return q + a();
}

4.c
extern int w;
int a();

int q()
{
  return w + a();
}
```

Program Headers:

<table>
<thead>
<tr>
<th>Type</th>
<th>Offset</th>
<th>VirtAddr</th>
<th>PhysAddr</th>
<th>FileSiz</th>
<th>MemSiz</th>
<th>Flags</th>
<th>Align</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOAD</td>
<td>0x0000000000000000</td>
<td>0x0000000000000000</td>
<td>0x0000000000000000</td>
<td>0x0000000000000794</td>
<td>0x0000000000000794</td>
<td>R E</td>
<td>200000</td>
</tr>
<tr>
<td>LOAD</td>
<td>0x0000000000000df0</td>
<td>0x0000000000000df0</td>
<td>0x0000000000000df0</td>
<td>0x0000000000000240</td>
<td>0x0000000000000240</td>
<td>RW</td>
<td>200000</td>
</tr>
<tr>
<td>DYNAMIC</td>
<td>0x0000000000000e10</td>
<td>0x0000000000000e10</td>
<td>0x0000000000000e10</td>
<td>0x0000000000000e10</td>
<td>0x0000000000000e10</td>
<td>RW</td>
<td>8</td>
</tr>
</tbody>
</table>

Section to Segment mapping:

[....]

Dynamic section at offset 0xe10 contains 24 entries:

[....]

Relocation section `.rela.dyn' at offset 0x480 contains 9 entries:

<table>
<thead>
<tr>
<th>Offset</th>
<th>Type</th>
<th>Info</th>
<th>Sym. Value</th>
<th>Sym. Name + Addend</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x000000200df0</td>
<td>R_X86_64_RELATIVE</td>
<td>680</td>
<td>_ITM_deregisterTMClone + 0</td>
<td></td>
</tr>
<tr>
<td>0x000000200df8</td>
<td>R_X86_64_RELATIVE</td>
<td>200e08</td>
<td><strong>gmon_start</strong> + 0</td>
<td></td>
</tr>
<tr>
<td>0x000000200e00</td>
<td>R_X86_64_RELATIVE</td>
<td>a + 0</td>
<td>__cxa_finalize + 0</td>
<td></td>
</tr>
</tbody>
</table>

Relocation section `.rela.plt' at offset 0x558 contains 3 entries:

<table>
<thead>
<tr>
<th>Offset</th>
<th>Type</th>
<th>Info</th>
<th>Sym. Value</th>
<th>Sym. Name + Addend</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x000000201018</td>
<td>R_X86_64_JUMP_SLO</td>
<td>680</td>
<td>_ITM_registerTMCloneTa + 0</td>
<td></td>
</tr>
<tr>
<td>0x000000200fe0</td>
<td>R_X86_64_JUMP_SLO</td>
<td>a + 0</td>
<td>_cxa_finalize + 0</td>
<td></td>
</tr>
<tr>
<td>0x000000200ff0</td>
<td>R_X86_64_JUMP_SLO</td>
<td>q + 0</td>
<td>__cxa_finalize + 0</td>
<td></td>
</tr>
</tbody>
</table>

[....]
What are all of the possible outputs of the following program?
In case you don’t list all of the possible outputs correctly, to improve opportunities for partial credit, show how you arrived at your answer by sketching one or more process graphs.

```c
#include "csapp.h"

int main() {
    pid_t pid1, pid2;
    int status;
    char buffer[1];

    pid1 = Fork();
    write(1, "F", 1);

    if (pid1 == 0) {
        exit(6);
    }

    pid2 = Fork();
    write(1, "S", 1);

    if (pid2 == 0) {
        exit(7);
    }

    Waitpid(pid2, &status, 0);
    buffer[0] = WEXITSTATUS(status) + '0';
    Write(1, buffer, 1);

    Waitpid(pid1, &status, 0);
    buffer[0] = WEXITSTATUS(status) + '0';
    Write(1, buffer, 1);

    return 0;
}
```
What are all of the possible outputs of the following program?

Again, to improve opportunities for partial credit, show how you arrived at your answer by sketching one or more process graphs.

```c
#include "csapp.h"

int main() {
    int fds[2];
    char buffer[1];

    Pipe(fds);

    if (Fork() == 0) {
        if (Fork() == 0) {
            Write(1, "2", 1);
            Write(fds[1], "5", 1);
            return 0;
        }
        Write(1, "1", 1);
        Read(fds[0], buffer, 1);
        return 0;
    }

    Write(1, "3", 1);
    Write(fds[1], "4", 1);

    return 0;
}
```
10. Consider a memory system with 16 bit virtual addresses, 16 bit physical addresses with a page size of 256 bytes. In the page table below, some entries are not listed; assume that those entries are all marked as invalid. For each of the following virtual addresses, indicate its physical address or indicate that it is a page fault.

<table>
<thead>
<tr>
<th>Virtual address</th>
<th>Physical address or page fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x3111</td>
<td></td>
</tr>
<tr>
<td>0x4161</td>
<td></td>
</tr>
<tr>
<td>0x00aa</td>
<td></td>
</tr>
<tr>
<td>0x0880</td>
<td></td>
</tr>
<tr>
<td>0x2198</td>
<td></td>
</tr>
</tbody>
</table>

VPN PPN/valid? VPN PPN/valid? VPN PPN/valid? VPN PPN/valid?
0x00 0x00/0 0x21 0x09/1 0x42 0x12/1 0x63 0x1b/1
0x01 0x08/1 0x22 0x11/1 0x43 0x1a/1 0xe0 0x07/0
0x02 0x10/1 0x23 0x19/0 0x44 0x22/1 0xe1 0x0f/1
0x03 0x18/1 0x24 0x21/1 0x45 0x2a/1 0xe2 0x17/1
0x04 0x20/1 0x25 0x29/1 0x46 0x32/0 0xe3 0x1f/1
0x05 0x28/0 0x26 0x31/1 0x47 0x3a/1 0xe4 0x27/1
0x06 0x30/1 0x27 0x39/1 0x48 0x42/1 0xe5 0x2f/0
0x07 0x38/1 0x28 0x41/0 0x49 0x4a/1 0xe6 0x37/1
0x08 0x40/1 0x29 0x49/1 0x4a 0x52/1 0xe7 0x3f/1
0x09 0x48/1 0x2a 0x51/1 0x4b 0x5a/0 0xe8 0x47/1
0x0a 0x50/0 0x2b 0x59/1 0x4c 0x62/1 0xe9 0x4f/1
0x0b 0x58/1 0x2c 0x61/1 0x4d 0x6a/1 0xea 0x57/0
0x0c 0x60/1 0x2d 0x69/0 0x4e 0x72/1 0xeb 0x5f/1
0x0d 0x68/1 0x2e 0x71/1 0x4f 0x7a/1 0xec 0x67/1
0x0e 0x70/1 0x2f 0x79/1 0x50 0x82/0 0xed 0x6f/1
0x0f 0x78/0 0x30 0x81/1 0x51 0x8a/1 0xee 0x77/1
0x10 0x80/1 0x31 0x89/1 0x52 0x92/1 0xef 0x7f/0
0x11 0x88/1 0x32 0x91/0 0x53 0x9a/1 0xf0 0x87/1
0x12 0x90/1 0x33 0x99/1 0x54 0xa2/1 0xf1 0x8f/1
0x13 0x98/1 0x34 0xa1/1 0x55 0xa9/0 0xf2 0x97/1
0x14 0xa0/0 0x35 0xa9/1 0x56 0xb2/1 0xf3 0x9f/1
0x15 0xa8/1 0x36 0xb1/1 0x57 0xba/1 0xf4 0xa7/0
0x16 0xb0/1 0x37 0xb9/0 0x58 0xc2/1 0xf5 0xaf/1
0x17 0xb8/1 0x38 0xc1/1 0x59 0xca/1 0xf6 0xb7/1
0x18 0xc0/1 0x39 0xc9/1 0x5a 0xd2/0 0xf7 0xbf/1
0x19 0xc8/0 0x3a 0xd1/1 0x5b 0xda/1 0xf8 0xc7/1
0x1a 0xd0/1 0x3b 0xd9/1 0x5c 0xe2/1 0xf9 0xcf/0
0x1b 0xd8/1 0x3c 0xe1/0 0x5d 0xea/1 0xfa 0xd7/1
0x1c 0xe0/1 0x3d 0xe9/1 0x5e 0xf2/1 0xfb 0xdf/1
0x1d 0xe8/1 0x3e 0xf1/1 0x5f 0xfa/0 0xfc 0xe7/1
0x1e 0xf0/0 0x3f 0xf9/1 0x60 0x03/1 0xfd 0xef/1
0x1f 0xf8/1 0x40 0x02/1 0x61 0x0b/1 0xfe 0xf7/0
0x20 0x01/1 0x41 0x0a/0 0x62 0x13/1 0xff 0xff/1
For the following two questions, a word is defined to be 16 bytes, each cell in a diagram represents a word, and an underlined number $N$ is a shorthand for $N$ times 16.

Assume that an allocator produces word-aligned payload pointers, uses a word-sized header and footer for each allocated block, uses a 2-word prolog block and a 1-word terminator block, coalesces unallocated blocks, and is confined to 18 words of memory that is initially filled with 0s. Show a header in a diagram as a value for the block size over a 0 or 1 to indicate the block’s allocation status; draw a footer as just the block size.

The left-hand column below contains a sequence of malloc and free calls that are handled by the allocator. Fill in the left-hand column by showing relevant header and footer values just after each step on the left. The first row of the left column is blank so that you can show the initial state of memory in the first row of the right column.

11. Show the state of memory after each step for an allocator that uses a first-fit allocation strategy, where the allocator searches from the start of an implicit free list.

\begin{verbatim}
11. Show the state of memory after each step for an allocator that uses a first-fit allocation strategy, where the allocator searches from the start of an implicit free list.

\begin{verbatim}
p1 = malloc(6)   p2 = malloc(4)   free(p1)   p3 = malloc(2)   p4 = malloc(2)   free(p2)   free(p4)
\end{verbatim}
\end{verbatim}
12. Show the state of memory after each step for an allocator that uses a **best-fit** allocation strategy, where the allocator finds the smallest unallocated block that matches the requested allocation size.

```
p1 = malloc(5)                   
p2 = malloc(1)                   
free(p1)                   
p3 = malloc(3)                   
free(p2)                   
free(p3)                   
```
**Answers**

1. **Access expression** | **Access address** | **Hit or miss**
--- | --- | ---
`s[0][0].a[0]` | 0xa0000 | miss
`s[0][0].b` | 0xa000c | miss
`s[0][1].a[0]` | 0xa0010 | miss
`s[0][1].b` | 0xa001c | miss
`s[0][2].a[0]` | 0xa0020 | miss
`s[0][2].b` | 0xa002c | miss

2. 100%

3. **Access expression** | **Access address** | **Hit or miss**
--- | --- | ---
`s[0][0].a[2]` | 0xa0008 | miss
`s[0][0].c` | 0xa000e | hit
`s[0][1].a[2]` | 0xa0018 | miss
`s[0][1].c` | 0xa001e | hit
`s[0][1].a[2]` | 0xa0028 | miss
`s[0][1].c` | 0xa002e | hit

4. 50%

5. **Cross out** x.c

6. **Output:** 7; y(ns) returns 5, z() returns 5, w() returns 2

7. **Cross out all except** 2.c

8. **Four possible outputs:** FFSS76, FSFS76, FSSF76, FSS7F6

9. **Two possible outputs:** 123, 213
10.

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</tr>
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<td>0x4161</td>
<td>page fault</td>
</tr>
<tr>
<td>0x00aa</td>
<td>page fault</td>
</tr>
<tr>
<td>0x0880</td>
<td>0x4080</td>
</tr>
<tr>
<td>0x2198</td>
<td>0x0998</td>
</tr>
</tbody>
</table>

11.

```
p1 = malloc(6)
p2 = malloc(4)
free(p1)
p3 = malloc(2)
p4 = malloc(2)
free(p2)
free(p4)
```
12.

|        |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|        | 2 | 2 | 1 | 5 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| p1 = malloc(5) | 2 | 2 | 7 |   |   |   |   |   | 7 | 8 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| p2 = malloc(1) | 2 | 2 | 7 |   |   |   |   |   | 7 | 3 | 3 | 5 |   |   |   |   |   |   |   |   |   |   |   |   |
| free(p1) | 2 | 2 | 7 |   |   |   |   |   | 7 | 3 | 3 | 5 |   |   |   |   |   |   |   |   |   |   |   |   |
| p3 = malloc(3) | 2 | 2 | 7 |   |   |   |   |   | 7 | 3 | 3 | 5 |   |   |   |   |   |   |   |   |   |   |   |   |
| free(p2) | 2 | 2 | 1 | 0 |   |   |   |   |   | 1 | 0 | 5 |   |   |   |   |   |   |   |   |   |   |   |   |
| free(p3) | 2 | 2 | 1 | 5 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | 15 | 0 |

*Shading above is not required in an answer.*